THESIS

THE IMPACT OF LAND USE CHANGE ON SOIL EROSION IN SERAYU WATERSHED, CASE STUDY MERAWU WATERSHED, BANJARNEGARA, CENTRAL JAVA

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ABSTRACT

Merawu watershed is the biggest sediment producer in upper Serayu watershed. It delivers about 1,450,000 m³ sediment every year. The high sediment is triggered by the composition of land use that is dominated by agricultural area which has thin vegetation cover such as vegetation croplands and agro-forestry area. This research was mainly aimed to assess the impact of land use change on soil erosion in Merawu watershed during the last 20 years. The land use change assessment was conducted by using Landsat TM 1994, Landsat ETM 2002 and Landsat OLI 2014. The result of land use change was used as inputs for soil erosion analysis. Soil erosion analysis was performed by using the Watem/Sedem erosion model. This study also analyzed tolerable soil loss and the effect of soil loss on crop productivity. Tolerable soil loss was assessed using local farmers' knowledge and annual soil erosion. And the effect of soil loss on crop productivity was assessed based on farmers' perception on their annual crop yield the last 20 years.

The analyses results showed that Merawu watershed was dominated by agricultural area; agro-forestry in the middle parts, vegetable cropland in the Northern part, plantation of salak (Salacca zalacca) and paddy field in the middle and the Southern parts of the basin. Since 1994, 50% of the land use has changed. Most changes took part within agricultural areas, from agro-forestry to vegetable cropland and vice versa. The Watem/Sedem simulation showed that the highest sediment occurred in 1994 (3,018,582 ton), the lowest occurred in 2002 (1,229,729 ton). In 1994, sediment delivery rose again up to 1,348,185 ton. The worst erosion occurred in range of 100 ton/ha/year to 500 ton/ha/year and > 500 ton/ha/year and appeared in the Northern and middle parts; in Pejawaran, Wanayasa, Batur, and Karangkobar Sub districts that were occupied by vegetable cropland and agro-forestry. The result of tolerable soil loss assessment showed that the tolerable soil loss was dynamic following annual soil erosion rate. Based on 400 years of erosion period, 25% area of Merawu watershed was in state of intolerable soil loss. Most of the catchment was dominated by tolerable soil loss in range of 2.6 mm/year to 5 mm/year and 0.1 mm to 2.5 mm with 38% and 30% respectively. Meanwhile, based on 25 years of erosion period, it was only 2.5% of the catchment area that was in state of intolerable of soil loss. The watershed area was dominated by tolerable soil loss in range of 20.1 mm to 40 mm/year. Meanwhile, the result of the assessment of soil loss on crop productivity revealed that farmers in Merawu watershed had not found the decline in crop productivity despite the detected area of intolerable soil loss.

Key words: land use change, soil erosion, tolerable soil loss, crop productivity

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1. INTRODUCTION

The relation between land use and water erosion has been explored by many studies (Shrestha, 1997;Morgan & Duzant, 2008; Sharma et al., 2011; Wijitkosum, 2012). Morgan & Duzant (2008) suggest that (in term of soil loss by water) the vegetation cover gives more prominent effect rather than soil properties. Forest canopy is effective in controlling runoff effect so that the erosion rate in forested area is much lower than the less vegetated area such as rainfed cultivation (Shrestha, 1997). The same thing is also found by Sharma et al., (2011) that the decrease of forest in India has increased erosion risk and forest is claimed to be an effective barrier for soil erosion.

Soil erosion intensity has a strong correlation with land use, even stronger than the relation between soil erosion and rainfall variability or slope (García-Ruiz, 2010; Kosmas et al., 1997; Pacheco et al., 2014). Vegetation cover that is inherently related to land use (Pacheco et al., 2014) is believed to be effective in reducing the energy of erosion driving force, especially from rain drops because plants and plant cover residues tend to slow down the movement of surface runoff and allow the excess of surface water to infiltrate into the ground (Morgan, 2005). The vegetation structural arrangement also gives huge influences on water balances and rates of erosion (Blanco & Lal, 2008). Single storey vegetation may not able to reduce the effect of rainfall energy as multiple storey forests do, because raindrop could regain its terminal velocity after being intercepted and cause soil detachment (Blanco & Lal, 2008).

As soil erosion has a strong correlation with land cover and land use, changes in land use or in vegetation cover percentage affects the amount of soil loss (Wijitkosum, 2012; Alkharabsheh et al., 2013). The effect of land use change on soil erosion depends very much on the type of changes happened to the land use. If land use change increases vegetation/forest cover and decreases agricultural activities, then sedimentation caused by soil loss will also decrease (Boix-fayos et al., 2008).

Basically, soil erosion is a natural process (Graaff, 1996). It becomes intolerable when it is accelerated by human and or the amount of soil loss affects soil quality and reduces crop productivity (Graaff, 1996; Mandal & Sharda, 2011). Further, it is called intolerable when it starts to reduce soil fertility, soil thickness, water storage capacity of soil and thus crop productivity (Li et al., 2009). In principle, the concept of tolerable soil loss (commonly expressed by T value) is a basis of judging erosion risk, productivity loss, sedimentation in a river downstream, soil quality and soil erosion control (Johnson,

1987; Li et al., 2009). Since it is directly correlated to soil erosion problem, therefore, information about soil loss tolerance limits can provide an early warning about the potential negative effect of continued soil erosion and its effect on land use and crop productivity (Li et al., 2009).

The prominent effect of land use change on soil erosion and soil loss makes land use monitoring is an urgent thing to do. In this sense, the use of remote sensing is very important because one of the main application of the satellite data is change detection, due to the repetitive coverage and consistent quality of the satellite images (Singh, 1984, 1989). Remote sensing makes it possible to apply techniques and technologies to detect the changes (Lu et al., 2011; Corner et al., 2014) such as the univariate image differencing, vegetation index differencing, image regression, image rationing, principal component analysis, post classification comparison, direct multi-date comparison, change vector analysis, and background subtraction (Singh, 1989). But satellite image interpretation as such provides information about land cover (i.e. that can be seen on the images), so, additional techniques and data are needed to derive land use information (Fonji & Taff, 2014).

The accelerated soil erosion and intolerable soil loss can cause an adverse impact both on site and off site. The on-site effect is mainly about loss of productivity which restricts what can be grown due to soil loss, the breakdown of soil structure, the decline in organic matters and soil fertility (Morgan, 2005). The off-site impact comes from sedimentation in downstream areas which decreases river capacity and thus triggers river flood, block irrigation and reduce reservoir lifespan. In addition, sedimentation can change the landscape characteristics, diminish the wildlife habitats, economic loss and many other (Blanco & Lal, 2008).

Many models have been developed and employed to assess, predict and monitor soil erosion under a wide range of conditions. In 1978, Universal Soil Loss Equation (USLE) was firstly introduced. USLE is an empirical model to predict soil loss on cultivated land in order to be able to determine erosion control (F.A.O, n.d.). The Revised USLE (RUSLE) was then introduced as an update of USLE (Renard et al., 1997). Morgan Morgan Finney (MMF) was another empirical model that was introduced in 1984 to predict annual soil erosion in field sized-area (Morgan et al., 1984). Beside empirical models, there are also some physical erosion models, such LISEM, and WATEM/SEDEM. Limburg Soil Erosion Model (LISEM) developed in the Netherlands was the first erosion model that was integrated in raster GIS (de Roo & Wesseling, 1996). It is an event-based erosion model in catchment scale (de Roo et al., 1999). And WATEM/SEDEM is a spatially distributed erosion and sediment transport model based on RUSLE model and also equipped with sediment transport equation to predict sediment delivery to a drainage network (Alatorre et al., 2012).

1.1. Research problem

Serayu Watershed on Java Island, Indonesia is seriously affected. A deforestation rate due to agricultural expansion in the upslope areas of the watershed is approximately 600 ha/year since 1997 Lavigne & Gunnel (2006). One of the suspected impacts is the acceleration of soil erosion. Evidence for this is very clear in the Mrica reservoir in the downstream part of the Serayu River catchment. The remaining effective the reservoir is only 67% due to sediment deposition (Soewarno & Syariman, 2008). Consequently, soil fertility loss, the decrease of soil thickness and crops yield are exported to occur.

See for example (Rustanto, 2010; Rudiarto & Doppler, 2013). Rudiarto & Doppler (2013) assessed land cover changes in Kejajar Sub District (upper part of Serayu watershed) a period of 10 years (1991 to 2001). They found out that, in 10 years, about 50% of the forest areas have been degraded and or converted to agricultural fields and or scrub lands. They concluded that these areas then appeared to have the highest erosion rate. Rustanto (2010) found that during 20 years (1989 to 2009) land use/land cover change has caused an increase of sedimentation in Panglima Besar Sudirman (Mrica) reservoir.

However, concerning the amount of soil loss from soil erosion in Serayu watershed, it is not yet known whether, and if so, where this is exceeding the tolerable soil loss limit. Setiawan (2012) has taken tolerable soil loss into account in his research in Kejajar sub District, Wonosobo (upper part of Serayu watershed), so far no information about tolerable soil loss is available at catchment scale.

Therefore, this research proposed to include tolerable soil loss concept in assessing the impact of land cover change on soil erosion. Tolerable soil loss or soil loss tolerance is defined as the maximum soil loss by erosion that allow optimum crop productivity (Wischmeier & Smith, 1978). It is the quantity of soil surface that can be reduced without decreasing crop productivity in function of time and position (Stamey & Smith, 1964). The assessment of tolerable soil loss was aimed to know whether soil loss dynamic caused by land cover change had exceeded the tolerable limit. In addition, the effect of soil loss on crop productivity trend was addressed to confirm whether the trend of crop productivity was in line with the soil loss hazard level (tolerable or intolerable).

For this purpose, Merawu watershed which is located in Serayu watershed was selected as the study area. Merawu watershed was selected because Merawu watershed is the highest sediment producer compared to the neighborhood catchments that is delivered to a reservoir in the downstream part of Merawu watershed (Sulistyo, 2011a). To assess the erosion hazard, the WATEM/SEDEM erosion model was applied. This model was applied because it is not too data demanding (Haregeweyn et al., 2013), and therefore it is suitable to be applied in Indonesia where input data is not always easy to obtain.

1.2. Objectives and research questions

1.2.1. Objectives

The main objective of this research was to assess the impact of land use change on soil erosion in Merawu watershed. In addition, the effect of soil loss on agricultural land uses was evaluated by applying the concept of tolerable soil loss. Specific objectives of this research were:

specific objectives of this research were.

- 1. To assess land use change for the period 1994 2014
- 2. To assess soil loss and sediment delivery for the current and past land use situation using the WATEM/SEDEM soil erosion model
- 3. To apply the tolerable soil loss concept to assess the effect of erosion (soil loss) on crop productivity in the study area.

1.2.2. Research questions

Based on the specific objectives, research questions which were addressed in this research were:

- 1. What is the trajectory of land use change during 1994 2014 in the study area?
- 2. How is the dynamic soil loss from 1994 to 2014 based on current and past land use situation?
- 3. What is the impact of land use change on soil erosion during 1994 to 2014, especially in forest and agricultural land use?
- 4. What is the spatial distribution of the tolerable soil loss in the study area based on present soil erosion?
- 5. What is the effect of soil loss on crop productivity in farmers' perception?

2. LITERATURE REVIEW

2.1. Land cover and land use change

The term of land cover originally referred the attributes of earth surface and subsurface including biota, soil, topography, water, and man-made structures. Meanwhile, land use refers to the purpose of land cover exploitation by human (Lambin et al., 2006). That's why land use can also be defined as the factors that cause land cover change (Lambin et al., 2006).

Land cover change comprises the shift a type of land cover to one or more cover types such as in the case of farming expansion, illegal logging, and or settlement extent (Lambin et al., 2006). At least, two causal factors cause land use change: proximate factors and underlying factors. Proximate (direct) factors are factors that directly trigger land cover change by physical action and it usually occurs locally (households or communities). Underlying factors are factors that strengthen the proximate ones and it happens in a more massive scale such as regional or global coverage. It may be promoted by politics, technology, social, biophysical aspects and many others (Lambin et al., 2006).

Land cover can also be shifted by forces other than by human. Natural factors may also initiate modifications upon land cover. However, land cover change mainly occurs by the involvement of human (Lambin et al., 2006). Figure **2.1** shows the relation of land use / land cover change and human activities.



Figure 2.1. Link between human activities and land cover/land use change Source: Lambin et al., (2006)

2.2. Remote sensing in land use change

2.2.1. Image correction

Image is a group of pixels with certain values that represents the amount of reflection or emission of spectral object recorded by censors (Danoedoro, 2012). It consists of group of pixels that represent realities with its value (Danoedoro, 2012). However, some errors (geometry and radiometry) may have occurred when the image data is recorded by censors (Richards & Jia, 1999). Positional errors come from dynamic position of satellite, rotation of earth, the movement of mirrors on censor's scanners, and also earth's shape. Whereas radiometric errors source from the inconsistency of detectors in capturing information that results anomaly of pixel's values and also from the interruption on satellite signal due to the malfunction of detectors in some certain periods (Richards & Jia, 1999). Therefore when an image is to be utilized, it is necessary to conduct geometry and radiometric correction attached in the image (Danoedoro, 2012). Image pre processing is necessary to establish direct linkage between the images and the biophysical phenomena, to remove image noise and data acquisition error since the image noise affects the change detection capabilities or even create false change phenomena (Coppin et al., 2004).

2.2.2. Image classification

Image classification (multispectral classification) is a method that is designed to derive thematic information that is mostly maps of land cover and land use by grouping phenomena by certain criteria (Danoedoro, 2012). On manual classification, some criteria are used such as the similarity of tone or color, texture, shape, pattern, relief and others which are applied as a whole set at the same time. But, in multispectral classification, only one criterion is used, namely spectral values (brightness value) in some bands at once (Danoedoro, 2012).

Two kinds of image classification are widely used, supervised and unsupervised classification. Supervised classification comprises a group of algorithms which are based on inputting object's sample (training area) (Danoedoro, 2012). Whereas, unsupervised classification lets the computer to group the pixels without being interfered by operator (human). This process is actually an iteration process until resulting in groups of spectral (Danoedoro, 2012).

The result of image classification is also a thematic map that needs to be validated (Danoedoro, 2012). The evaluation of accuracy of the classification can be applied in two aspects: the depth of information (detail of information) and truth in reality

(Danoedoro, 2012). Accurate results of image classification with the reality equals to accuracy of land cover and land use compare to real ground cover (Danoedoro, 2012).

2.2.3. Accuracy assessment of image classification

Accuracy assessment is the key to spatial data related work (Congalton, 2001). Accuracy assessment is needed to know the reliability of the image classification in order to be able to compare quantitatively with other methods, and in order to be able to use in some analysis and decision making process (Congalton, 2001).

One of the technique for the accuracy assessment is quantitative accuracy assessment (Congalton, 2001). The key in quantitative accuracy assessment is the application of error matrix (Congalton, 2001). An error matrix is an effective way in describing the accuracy because the error matrix describes both commission and omission error for each class (Congalton, 2001). The other method of accuracy assessment that still makes use of error matrix is KAPPA (Congalton, 2001). It ranges from +1 to -1 (Congalton, 2001).

2.2.4. Land use change detection

Change detection is the process of identifying differences of an object or phenomenon by observing it at different times (Singh, 1989). Essentially, it involves the ability to quantify temporal effects using multi temporal data sets (Singh, 1989). Many change detection methods have been developed and used for various applications. However, they can be broadly divided into two approaches: post-classification and spectral change detection (Xiuwan, 2002).

Post classification is the most widely applied techniques for change detection purpose. Main advantage of post classification is a tabulation of from and to information of land use change. Therefore, it enables to analyze of images at different periods of time and even different censors. But, the dependency to individual classification accuracies must get to attention since it can contribute to a large number of erroneous change indications (Singh, 1989). Therefore, the individual classification must be as accurate as possible (Xiuwan, 2002).

Spectral change detection techniques are based on primary assumption that the result of land use change gives stable changes of spectral reflectance (Xiuwan, 2002). It performs the transformation of two images into new images with one or multiband image. Most of these techniques are based on some types of image differencing or rationing. The changes are detected by subtracting images from two different period of time (Singh, 1989).

2.3. Soil erosion

Soil erosion is the result of detachment, transport and deposition process (Panizza, 1996). It is a hazard traditionally associated with agriculture in tropical and semi arid areas and it influences the productivity and the sustainability of agriculture in long terms (Morgan, 2005). The word "erosion" initially came from Latin word "to erodere" which means to eat away, and to excavate. Later, the term erosion is used to describe all form of destruction of earth's surface due to water (Zachar, 1982).

Zachar (1982) differentiated the kind of erosion into two groups, natural process and anthropogenic process. In natural condition where there are not any anthropogenic activities, the soil productivity remains constant and the erosion is in equilibrium (acceptable limit). If anthropogenic activities interfere with practice of agriculture but it is done by applying conservation technique, the effect on soil erosion can still be zero (nil hazard). However, the equilibrium can be altered if an exceptional natural events occur, such as heavy rainfall, long period of drought, earthquake, landslide, etc, abnormal erosion can be triggered. And when the abnormal condition runs into anthropogenic activities (deforestation, non conservative farming, earth-moving, etc) soil erosions will be accelerated (Panizza, 1996)



Figure 2.2. The relationship between soil erosion type and related hazard levels Source: Panizza, (1996)

The effects of erosion in general are grouped into two kinds: on site effects and off site effects (Morgan, 2005). The on-site effects comprise the loss of soil, the damage of soil's structures, the decline in organic matters, the loss of soil moisture which leads to more drought prone condition, the reduction of soil fertility which impact on the reduction of cultivable land and the restriction of plantation that can be grown and result in the increase of expenditure for fertilizer. The off-site effects arise from the

sedimentation downstream and downwind which reduces the capacity of rivers and ditches and lead to the increase of flood risk, and many more even soil erosion can end up with contributor of climatic change through the breakdown of soil aggregates and clods into their original form of clay, silt and sand. This process will release the carbon held by the sedimentation (soil) into the atmosphere as CO2 (Morgan, 2005).

2.3.1. Erosion process

Morgan (2005) stated that the process of the erosion completes two phases. They are the detachment of soil particles from soil mass and the transporting of soil particles by erosive agents.



Figure 2.3 The flow chart of Soil Erosion by water Source: Morgan (2005)

During a rainstorm, either because there is no vegetation or because it passes through gaps in the plant canopy, part of the water falls directly on the land. Part of the rain is intercepted by the canopy, and returns to the atmosphere by evaporation or finds its way to the ground by dripping from the leaves, or by running down the plant stems as stemflow. The action of direct through-fall and leaf drainage produces rain-splash erosion. The rain that reaches the ground may be stored in small depressions or hollows on the surface or it may infiltrate the soil, contributing to soil moisture storage. When the soil is unable to take in more water, the excess contributes to runoff on the surface, resulting in erosion by overland flow or by rills and gullies (Morgan, 2005).

2.4. Land use change and soil erosion

Land use change has been acknowledged as one of the prominent trigger of world's environmental shift (Schosser et al., 2010). It is emerging as one of the most

urgent issues (Han et al., 2007). Regardless the socio economic advantage, land use change possesses unintended consequences on natural environment (Leh., 2013). In regional scale, the effect of land use change can induce biodiversity loss, decreasing of land fertility, land and water contamination, and the lowering of the ground water tables (Schosser et al., 2010). It is also known to affect the regional climate and water quality (Stohlgren et al., 1998; Zampella & Procopio, 2009; Leh et al., 2013).

In term of soil erosion, the role of land use/land cover was highlighted by Morgan (2005) that vegetation cover is able to neutralize the effect of precipitation on soil erosion. The change in land cover has caused the acceleration of the erosion, such as the clearance of the dense forest into agricultural land has increased soil erosion 3000 times (Morgan, 2005). In this following table (Morgan, 2005), the differences of annual soil erosion rate (t/ha) caused by land cover/land use change from natural condition to cultivated area and bare land.

	Natural	Cultivated	Bare soi
China	0.1–2	150–200	280–360
USA	0.03-3	5-170	4–9
Australia	0.0-64	0.1-150	44–87
Ivory Coast	0.03-0.2	0.1-90	10–750
Nigeria	0.5-1	0.1-35	3–150
India	0.5-5	0.3-40	10–185
Ethiopia	1–5	8-42	5–70
Belgium	0.1-0.5	3–30	7–82
UK	0.1-0.5	0.1-20	10–200

Table 2.1. Soil erosion rate under different land cover

2.5. Soil erosion modeling

Erosion modeling is necessary to deal with how much time needed to do field measurement of soil erosion. Not only is it very time consuming to build sufficient database, but also it is difficult to study the respond of land use change and climate or even the erosion control over long time of period if the measurement is conducted in the field (Morgan, 2005). To overcome these deficiencies, models are used to predict erosion under a wide range of conditions. The results of the predictions can be compared then with the measurements to ensure their validity (Morgan, 2005).

Erosion modeling was first introduced in 1978 by Weischmeir and Smith, which is the result of analyzing 10000 annual records of erosion on measurements plots and small catchments which is on cultivated fields (F.A.O, n.d.). It was an empirical model which is called Universal Soil Loss Estimation (USLE). Some other empirical models later on were developed such as RUSLE (Revised Universal Soil Loss Equation), which

Source: (Morgan, 2005)

is the improvement of USLE (Renard et al., 1997), Morgan-Morgan Finney which is the erosion modeling on field scale (Morgan et al., 1984), and RMMF (Revised Morgan-Morgan Finney) (Morgan & Duzant, 2008). Beside empirical models, some physical models are available also such as LISEM (Limburg Soil Erosion Model) (de Roo et al., 1999; Takken et al., 1999; Sheikh et al., 2010), and Watem/Sedem (Van Oost et al., 2000) that is also used in this research.

2.5.1. The WATEM/SEDEM model

WATEM/SEDEM (Water and Tillage Erosion Model and Sedimentation Delivery Model) is a sediment delivery model that predicts the amount of the transported sediment to a channel annually. The model is pixel-based with resolution 20m x 20m (van Oost et al., 2002). It is RUSLE-based model that takes into account the two dimensional of LS (topography factor) calculation where slope length is replaced with unit contributing area (van Oost et al., 2002). Since it is RUSLE-based model, some of the model input layers required are from RUSLE, such as crop management factor (C factor in RUSLE), land use, river map, roads, soil erodibility (K value in RUSLE), a digital elevation model (DEM), and pool, ponds or reservoir maps if exist (van Oost et al., 2002).

It has three components: 1) soil loss assessment, 2) sediment transport capacity assessment, 3) and sediment routing (Rompaey et al., 2001; Haregeweyn et al., 2011). Annual transport capacity is calculated by assuming it is proportional to flow erosion potential by applying a transport capacity coefficient (van Oost et al., 2002). Run-off pattern is calculated by considering the effect road and infrastructures with multiple flow algorithm (van Oost et al., 2002). The sediment routing is accounted by employing a routing algorithm to transport the sediment from the detachment place to the river (Haregeweyn et al., 2011). When the sediment reach the river, it is directly delivered to the catchment outlet (van Oost et al., 2002). Following the flow route, the sediment is transported down slope if the local transport capacity is more than the amount of the sediment volume. If the local transport capacity is less than the sediment, then the deposition takes place (Haregeweyn et al., 2011).

Model calibration is conducted by changing Transport Capacity coefficient (KTc) for different land use types (Haregeweyn et al., 2013). The transport capacity reflects the sensitivity of model to runoff and sediment delivery (Schmengler, 2010). Watem/Sedem model provides two kinds of Transport Capacity coefficient (KTc), KTc low and KTc high. KTc low ranging from 10 to 100, was given for vegetated areas and KTc high was given for poorly vegetated areas. It ranged from 30 to 300 (Schmengler, 2010).

2.6. Tolerable soil loss

Soil erosion modeling results in erosion rate simulation and or estimation. The next step is to know whether the erosion rate is accelerated or in natural condition by using the concept of tolerable soil loss (Setiawan, 2012). Tolerable soil loss, or soil loss tolerance, or permissible soil loss is needed to preserve the soil productivity and environmental security for a long term (Li et al., 2009).

Soil loss tolerance or tolerable soil loss is the maximum level soil loss can experience, and, also still maintain the soil quality (in term of crop productivity) (Wischmeier and Smith, 1978). This concept was proposed by Smith (1941) as quantitative criterion for establishing soil erosion management (Duan et al., 2012). The tolerance values serve as major criterion as erosion control (Li et al., 2009; Alewell et al., 2014;). The definition of soil loss tolerance at least has to fulfill five things (Stamey & Smith, 1964):

- 1. Provide for the permanent preservation or improvement of the soil resource
- 2. Adaptable to the erosion and renewal rates of any soil characteristics
- 3. A function of position since erosion and renewal rate should not be an uniform value
- 4. Applicable regardless of the cause of erosion and renewal
- 5. Based on the assumption that if the excess of the soil depth is available, it is tolerable to use the excess.

Duan et al (2012) grouped the soil loss tolerance assessment based on 1) soil formation rate, 2) soil thickness, and 3) soil productivity. Whereas, Li et al (2009) suggested at least there are three groups of method of determining the tolerable soil loss: 1) the amount of soil loss that equals to the soil formation rate, 2) maximum soil loss that will not reduce the crop productivity in long period, and 3) the maximum of soil loss that will not deteriorate the quality of soil and water off-site and on-site. T value (tolerable soil loss) based on soil formation rate is the T value that is less than and equal to soil renewability. T value based on crop productivity refers to the duration of expected productivity and soil loss maximum that will not lower the productivity over a long period. And T value based on the quality of water and soil refers to the amount of soil loss that will not the contaminate water and reduce soil quality off-site and on-site. This relates to some substances and material that may be found in the water and soil, such as fertilizer, pesticides, and other pollutants (Li et al., 2009).

3. STUDY AREA

Merawu watershed is one of the most sediment producers in Serayu River basin. Sediment records in Panglima Besar Sudirman reservoir, a reservoir in Serayu basin, proclaimed this watershed as the biggest contributor of sediment (Sulistyo, 2011b, 2011c). It delivers about 120,000 m³ sediment deposits every month and about 1,450,000 m³ per year to Serayu River (the result of data sediment analysis collected from PT. Indonesia Power). Figure 3.1 shows the highest sediment occurs in December to March while the lowest occurs in June to October.



Figure 3.1. The average of sediment deposits from Merawu per month (m³) since 2006 to 2014 as recorded in the Merawu outlet. Source: PT. Indonesia Power.

Merawu Watershed which is about 23,350 ha, stretches from the Northern part to the Southern part of the upper Serayu Watershed. Administratively, it is situated in Banjarnegara District, Central Java Province. The watershed comprises 8 Sub Districts as indicated in Table 3.1 and Figure 3.2. Table 3.1 shows that the largest coverage within Merawu watershed is Wanayasa Sub district and the smallest is Madukara Sub district.

Table 3.1. Merawu watershed area based on the sub districts coverage

Sub Districts	Area (Ha)
Madukara	1279.5
Banjarmangu	1299.3
Karangkobar	3166.7
Pagentan	1874.5
Pejawaran	4010.0
Batur	1493
Wanayasa	8555.5
Kalibening	1670



Figure 3.2. Map of Merawu watershed based on administrative boundaries Source: Map analysis

3.1. Geological setting and landforms

Merawu watershed is considered to have highly unstable rocks. They consists of blueish marls and mudstones with few calcareous beds and tuffaceus sandstones (R. Zuidam, Meijerink, & Verstappen, 1977). It was formed by rocks from pre-tertier to quarter ages through volcano eruption and alluvial sedimentation (Sulistyo, 2011a).

According to Bemmelen's classification on Java Island (1949), Merawu watershed lies on middle part that consists of mountainous area that is formed by Dieng Plateau and Northern Serayu Mountain (Jatiningtyas, 2012).

Merawu watershed is formed by several geological formations. The largest formation is Gunung Api Jembangan (Jembangan volcano) as indicated by Table 3.2. It is mainly located in the upstream and in the middle part of the catchment that formed about 51% area of Merawu watershed. The Halang formation is found in Karangkobar and Pagentan Sub districts, stretching from the northern part of the catchment to the downstream part as showed by Figure 3.3. It occupied about 16% of the catchment area. Dieng Volcano formation is found in southern Wanayasa and northern Batur sub district. It formed about 15% of the catchment. The other formations are relatively small.

No	Geological formation	Area (ha)
1	Jembangan Volcano Rocks	11545
2	Halang Formation	3644
3	Dieng Volcano Rocks	3234
4	Breccia Rocks	2598
5	Rambatan Formation	580
6	Kalibiuk Formation	485
7	Alluvial and others	1262

Table 3.2. Geological Formation of Merawu watershed

Source: Geological Agency



Figure 3.3. Map of Geological Formation Source: Geological Agency

Eight landforms are identified in Merawu watershed: structural plateau in Karangkobar, Sibebek and Batur and Wanayasa, structural depressed in Kalibening, Balun, Karangkobar, Penusupan and Ratamba and near Pagentan, flood plains in Merawu river confluence with Serayu river, planatation surface in soft sedimentary rocks around Karangkobar, denudational hills in Sibebek (Wanayasa Sub District) and Batur due to dissection of volcanic foot slopes, steep slopes, severe mass wasting, deep soil weathering, thick efflata layers on top of marls and clays and tectonic activity together with human activities, lava field and lahar deposits in Batur (Zuidam et al., 1977).

The relief varies from flat, undulating, rolling, hilly and mountainous as indicated in Appendix 19. The upstream of the watershed is dominated by hilly to mountainous. This area is mostly steep. Whereas in the middle part is dominated by undulating rolling, and flat in the downstream.

This watershed is dominated by volcanic process in the upstream part, and structural process in the middle stream part as showed by Figure 3.4. In the middle part, denudation is also detected. Meanwhile, the downstream part is dominated by fluvial process. The distribution of geological processes based on geomorphological units is presented in Table 3.3.

No	Code	Relief	Process	Lithology
1	f.fluv.1	Flat or almost flat	Fluvial	Alluvial
2	h.stru.2	Hilly-steeply dissected	Structural	Breccia
3	s.stru.3	Steeply dissected-mountainous	Structural	Clastic sediment
4	r.stru.2	Rolling-hilly	Structural	Breccia
5	h.stru.3	Hilly-steeply dissected	Structural	Clastic sediment
6	r.stru.2	Rolling-hilly	Structural	Breccia
7	s.stru.2	Steeply dissected-mountainous	Structural	Breccia
8	h.stru.2	Hilly-steeply dissected	Structural	Breccia
9	h.stru.3	Hilly-steeply dissected	Structural	Clastic sediment
10	h.stru.3	Hilly-steeply dissected	Structural	Clastic sediment
11	h.den.5	Hilly-steeply dissected	Denudational	Lava
12	h.den.2	Hilly-steeply dissected	Denudational	Breccia
13	u.stru.3	Undulating-rolling	Structural	Clastic sediment
14	s.stru.5	Steeply dissected-mountainous	Structural	Lava
15	r.stru.4	Rolling-hilly	Structural	Marl
16	u.stru.5	Undulating-rolling	Structural	Lava
17	h.den.5	Hilly-steeply dissected	Denudational	Lava
18	h.vol.4	Hilly-steeply dissected	Volcanic	Marl
19	h.stru.5	Hilly-steeply dissected	Structural	Lava
20	h.vol.5	Hilly-steeply dissected	Volcanic	Lava
21	u.stru.5	Undulating-rolling	Structural	Lava
22	s.stru.5	Steeply dissected-mountainous	Structural	Lava
23	h.vol.5	Hilly-steeply dissected	Volcanic	Lava
24	r.vol.5	Rolling-hilly	Volcanic	Lava
25	s.vol.5	Steeply dissected-mountainous	Volcanic	Lava
26	u.vol.5	Undulating-rolling	Volcanic	Lava

Table 3.3. Geomorphological unit of Merawu watershed

No	Code	Relief	Process	Lithology
27	h.vol.5	Hilly-steeply dissected	Volcanic	Lava
28	h.vol.5	Hilly-steeply dissected	Volcanic	Lava
29	s.vol.5	Steeply dissected-mountainous	Volcanic	Lava
30	s.vol.5	Steeply dissected-mountainous	Volcanic	Lava
31	h.vol.5	Hilly-steeply dissected	Volcanic	Lava
32	s.vol.5	Steeply dissected-mountainous	Volcanic	Lava

Source: Geological Agency



Figure 3.4. Map of Geomorphological Units Source: Map analysis and Geological Agency

3.2. Present land cover and land use

The detail present land use is shown by Table 3.4 and Figure 3.5. Merawu watershed is dominated by vegetable croplands in the northern part which are planted with potatoes, carrot, cabbage, tomatoes, and other kinds of vegetables. Whereas in the middle part is dominated by agricultural area other than vegetables like corns, cassava mixed with some kinds of plantation such as albasia (*Paraserianthes falcataria*), bamboo and others. *Salaca zalacca* (salak) plantation dominates the middle part to the southern part like in Pagentan and Madukara Sub districts beside paddy field in the flat area in the bank of Merawu River. In addition some dense forest is also identified in some part of the watershed like in the tip of northern part and in middle part of the river basin. The forests mostly belong to the Government and are dominated by Pine trees.

No	Land use types	Area (%)	Area (ha)
1	Agro-forestry	39.6	9255.1
2	Settlements/Infrastructures	6.0	1411.9
3	Vegetable croplands	20.5	4777.4
4	Plantation Forest (Pine forest)	6.4	1500.4
5	Paddy Field	4.3	1010.9
6	Plantation	17.3	4042.9
7	Shrub rangeland	5.8	1361.9

Table 3.4. Present land use in Merawu watershed

Source: The result of Landsat OLI 2014 classification



Figure 3.5. Present land use of Merawu watershed

3.3. Soil

Merawu watershed is dominated by Latosol, Grumusol and Andosol soil types. Another soil types is Litosol which is in small coverage. Andosol can be found in Batur, Pejawaran and middle part of Wanayasa Sub district. Latosol covers Northern part and Southern part of Wanayasa, Northern part of Karangkobar, Eastern part of Kalibening and Pagentan Sub districts. Grumusol is mostly in Southern part of Karangkobar, Pagentan, and Madukara, and Banjarmangu Sub districts. Meanwhile, Litosol can be found in Banjarmangu in small fraction. The coverage area and the spatial distribution are presented in Table 3.5 and Figure 3.6.

No	Soil Types	Area (ha)	Percentage (%)
1.	Grumusol	3897.3	16.7
2.	Litosol	135.6	0.6
3.	Andosol	9073.5	38.8
4.	Latosol	10241.9	43.9

Table 3.5. Soil types and the coverage area

Source: Balai Sabo Yogyakarta, Ministry of Public Work



Figure 3.6. Map of Soil Types, Merawu watershed Source: Balai Sabo Yogyakarta, Ministry of Public Work

3.4. Climate and rainfall

The climate type of merawu watershed based on Schmidt and Fergusson is dominated by wet climate with high intensity of rainfall (Jatiningtyas, 2012). The number of wet months is more than the dry months with only 4 months/per year. The dry months usually occur in June to September, while months with the highest intensity rainfall occur in November to march. Rainfall intensity per month varies from 50 to 550 mm. The highest rainfall intensity occurs in December with about 550 mm/month. And the least rainfall intensity usually occurs in August and September with 50 to 60 mm/month. The trend of rainfall intensities per month is showed by Figure 3.7.



Figure 3.7. The average of monthly rainfall during 1989 to 2014 Source: the result of analysis of rainfall data from 1989 to 2014

The rainfall intensity corresponds with river discharge in Merawu river outlet. The peak of water discharge occurred in January, February, March and December with 650 m³/sec to 700 m³/sec as presented in Figure 3.8.



Figure 3.8. Monthly river discharge of Merawu river from 2006 to 2014 Source: PT. Indonesia Power

4. METHODOLOGY

4.1. Research approach

The main goals of the research were to identify the impact of land use change on soil erosion, to identify tolerable soil loss and the impact of soil loss on soil productivity. For those purposes, this research consisted of four main parts: 1) land use change analysis, 2) soil erosion assessment, 3) tolerable soil loss assessment, and 4) the impact of soil loss on crop productivity assessment. Land use change was analysed by utilizing Landsat images. Soil erosion was modeled by using the Watem/Sedem erosion model, the tolerable soil loss was assessed based on the knowledge of local farmers and annual soil erosion rates, and the impact of soil loss on crop productivity was assessed based on farmers' perception. The research framework is presented in Figure 4.1.

4.2. Data

This research applied two kinds of data: secondary data and primary data.

4.2.1. Secondary data

Secondary data that were used in this research is tabulated in Table 4.1 below:

Dataset	Year	Format	Scale	Sources
Daily rainfall data	1989 to	Digital excel	-	Water resources management
	2014			Agency of Banjarnegara
				District and Meteorological
				and Climatology Agency of
				Indonesia
Topographic map	2012	Digital vector	1:25,000	Geospatial Information
		format		Agency of Indonesia (Badan
				Informasi Geospasial)
Soil textures	2012	Digital excel	-	(Jatiningtyas, 2012)
		format which		
		is the result of		
		laboratorium		
		analysis.		
Landsat Images	1994,	Digital raster	-	www.earthexplorer.usgs.gov
(detail explained	1997,			
in other	2002,			
subsection)	2014			
Google earth	2014	Digital Raster	-	Google Earth
image				
Sedimentation	2006 to	Digital excel	-	Indonesia Power, Mrica
record of Merawu	2014			
outlet				

Table 4.1. Secondary data tabulation



Figure 4.1. Research framework

4.2.1.1. Daily rainfall data

Daily rainfall data was collected from two sources: the Water Resources Management Agency Banjarnegara District and the Climatology and Geo-meteorology Agency of Indonesia. The data came from eight rainfall stations. The position of the rainfall stations is showed by Figure 4.2. However, not every stations data were available during 1989 to 2014. Hence, the three year-periods of analyses had to use different number of rainfall stations data:

- 1. Analysis in 1994 utilized 6 rainfall stations (Pejawaran, Wanadadi, Limbangan, Banjarnegara, Clangap, Banjarmangu)
- 2. Analysis in 2002 involved 7 rainfall stations (Pejawaran, Wanadadi, Limbangan, Banjarnegara, Clangap, Banjarmangu, Karangkobar)



3. Analysis in 2014 involved 8 rainfall stations (Pejawaran, Wanadadi, Limbangan, Banjarnegara, Clangap, Banjarmangu, Kalilunjar).

Figure 4.2. Map of rainfall stations in and surrounding Merawu watershed

4.2.1.2. Landsat images

The Landsat images were acquired freely from www. http://earth.explorer.usgs.gov. They were retrieved from path 120 and row 65. And all images were already geometrically corrected. All of the images were considered to be in dry season. Table 4.2 shows the acquisition date of the Landsat images.

Acquisition date	Landsat series
30 August 2014	OLI
17 May 2002	ETM+
30 Juli 1997	TM
29 June 1994	ТМ

Table 4.2. Landsat images acquisition information
4.2.1.3. Soil data

Soil data were collected from Jatiningtyas (2012) whose data was part of her M.Sc Thesis. The data consisted of soil texture that followed USDA classification and the percentage of the fraction which were the result of laboratory analysis. The position of the soil data is indicated by Appendix 3.

4.2.2. Primary data

Primary data that were collected and analyzed in this research were (Table 4.3):

Dataset	Data collection method	Number of samples	Sample collection technique
Minimum soil depth needed for growing crops and maximum depth of soil that is considered fertile from the top of soil surface by farmers	Interview	43	Purposive sampling
Land use references	Visual observation	337	Purposive sampling
Farmers perspective on their crop productivity trend during the last 20 years	interview	43	Purposive sampling

Table 4.3. Primary data

In gaining primary data, purposive sampling data has been conducted. Purposive sample was selected because of the rough topography. The sampling was taken by considering the geomorphological units of study area that has been mapped before the field work (Figure 3.4).

4.2.2.1. Minimum soil depth for growing crops and maximum soil depth considered to be fertile by farmers.

A set of interview has been conducted to the farmers related to the minimum soil depth they need for their crops and maximum of soil depth in their field that they considered to have good fertility for crop to grow. The interviewees were selected purposively by considering the farmers age. The selected farmers were the farmers that were 35 years old and older. It was considered that by that age, the farmers have possessed adequate experiences in giving good answers since most of the farmers have started cultivating their lands since they were 15 years old.

43 samples succeeded to be collected. The maximum soil depth was mapped following geomorphology units. The minimum soil depth was mapped based on land use types because the minimum soil depth for growing crops depended on the type of crops or plantation the farmers were planting. For the minimum soil depth, all samples were groups based on the location of the samples whether they were in vegetable croplands, plantation, agro-forestry, and paddy field. For plantation forest and shrub which have no samples, value of 0.8 m was used. This value was the approximate value of soil depth needed for pine forest (Tejedor et al., 2004). Settlements/Infrastructures land use type was given 0. The distribution of the samples is indicated by Figure 4.3.

Two basic questions of the interview were:

- 1. What is the minimum of soil depth needed in growing good crop?
- 2. What is the maximum soil depth that is considered fertile for cropping?



Figure 4.3. Map of interview samples position

4.2.2.2. Land use references data

Land use references data were collected in the field by visual observation. 299 land use references were collected. Then some other data had to be collected from satellite images by applying Google earth satellite image to get shrub rangeland land use references that cannot be collected directly from the field because of its location in the sloping hill. They could be clearly seen visually from the distant, but could not be reached in the field. Hence, digital plotting through Google Earth images of year 2014 was applied. The number of land use references collected from satellite images was 38. Total references land use was 337. From all the references, 34 samples points were used as guides in taking training sample and the other 303 were used for the accuracy assessment. The land use references for accuracy assessment and the guide for taking the training samples are presented in Table 4.4 and Table 4.5.

	J
Land use references	Number of references
Agro-forestry	60
Built up area	75
Vegetable cropland	49
Plantation forest	29
Paddy field	27
Plantation	25
Shrub rangeland	38
Total	303

Table	24.4.	Land	use	referenc	es for	accuracy	assessment

Table 4.5. References data used for training s			
	Number references used		
Land use	as training samples		
	guides		
Agro-forestry	7		
Built up area	6		
Vegetable cropland	6		
Plantation forest	4		
Paddy field	3		
Plantation	4		
Shrub rangeland	4		

Table 4.5. References data used for training samples

4.3. Land use change assessment (1990 – 2014)

The land use change assessment was undertaken through steps presented by the diagram below (Figure 4.4).



Figure 4.4. Land use change assessment steps and data

4.3.1. Image pre processing

Image pre processing steps that were applied were radiometric correction that included: conversion of image Digital Number to at sensor radiance, and conversion of censor radiance value to Top of Atmospheric reflectance and haze reduction by applying Dark Object Subtraction (DOS). All of the processes were conducted by utilizing ENVI 5.1 Remote Sensing software.

4.3.2. Image classification for land cover year 2014

Image-based classification for land cover 2014 was conducted by applying Maximum likelihood classifier of supervised classification. It was conducted in ENVI 5.1 Remote Sensing software.

Image classification was conducted by: 1) taking sufficient training samples, 2) checking if there were overlapping classes, and 3) applying maximum likelihood classifier in Envi 5.1 Remote Sensing software. For field survey guidance, the image was

classified into 5 classes of land cover types. The classes were forested area, paddy field, dry agriculture, mixed vegetation and built up area.

The collection of field land use references was conducted by taking samples purposively by considering the representation of the all land use types. After the result of the ground check, the image was classified again and the class was converted into land use by considering the observed uses of the land by the people. The conversion was done as below:

- 1. Forested area was converted to plantation forest, by seeing the fact that most of the forested areas are homogenous planted pine forests.
- 2. Mixed vegetation was divided into several land use classes: agro-forestry, plantation (Salacca zalacca and *Paraserianthes falcataria*), and shrub rangeland. Agro-forestry was the use of lands for mixed agricultural products (such as maize, cassava) with tress (such as bamboo, Albasia (*Paraserianthes falcataria*). Plantation was the use of land for salak (*Salacca zalacca*) mixed with Albasia (*Paraserianthes falcataria*). Shrub rangeland was derived from the dominated shrub land cover type which was uncultivated.
- 3. Settlements/Infrastructures were all land cover types that were built and paved by people for settlements, government facilities, and markets. Since, it was impossible to differentiate those three kinds of land use types in Landsat images, they were grouped into one land use type called Settlements/Infrastructures.
- 4. Paddy field was all land use intended to produce paddy, both irrigated and rain-fed.

4.3.3. Image classification 2014 accuracy assessment

Four types of accuracies were assessed: producer's accuracy, user's accuracy, overall accuracy and Kappa coefficient. The accuracy assessment was conducted by using confusion matrix. An error matrix is an effective method of assessing categorical data because in an error matrix all of the accuracy of each categorical data presented with commission error and omission errors (Congalton, 2001). And Kappa statistics was performed because land use map were categorical datasets and Kappa could be used to compute agreement between a pair of maps (Foody, 2002; van Vliet, Bregt, & Hagen-Zanker, 2011; Wilkinson, 2005).

4.3.4. Older images land use classifications

Since older land use references were not available to check the accuracy of older images (1994, 2002), older images were classified by applying the end-members of the classified image 2014. The training sample used for 2014 image, was then used for image

2002 and 1994. However, to prevent the end members fell on the changed pixels, each end member position was observed thoroughly. If training samples fell on the changed pixels, adjustments were undertaken. Maximum likelihood classifier was also applied as on image 2014. Before being classified, the images had been calibrated radiometrically (conversion of Digital Numbers to at sensor radiance and conversion of radiance to Top of Atmospheric reflectance, and haze reduction by applying Dark Object Subtraction to prevent differences in reflectance value and haze noise among the images. All of the processes were undertaken in Envi 5.1 Remote Sensing software.

Since about 10% of image 1994 was covered by cloud, the image 1994 was masked by using image 1997. The use of image 1997 was due to the unavailability of other images acquired in 1994 that could be applied to mask the cloud.

4.3.5. Land use change detection rationality assessment

Land use change rationality assessment was undertaken because of the absence of reference data for image classification of 2002 and 1994. Therefore, the classification accuracy for image 2002 and 1994 could not be conducted. In order to be able to justify the accuracy of the temporal image classifications, the rule-based rationality change detection evaluation by Liu & Zhou (2004) was applied. For this rationality change detection assessment, 300 random points was taken from the result of image classifications. The overall accuracy was calculated from the total number of true (correctly classified) pixels based on the rules (Liu & Zhou, 2004) as following:

- 1. If the sample pixel is classified to be the same land use for all dates, then it is regarded to be correctly classified
- 2. If one change only is detected from a land use type (except settlements/infrastructures) into another land use type, the sample pixel is regarded to be correctly classified.
- However, if one change is detected from settlements/infrastructures to other land use types, the pixel is regarded not correctly classified because settlements/infrastructures class is regarded irreversible.
- 4. If a pixel is detected to change from a land use type (LU1) into another land use (LU2) and reverses back to the first land use type (LU1), it is regarded as the fuzzy state. Because it can be caused by the error of the classification and it also can truly happen.
- 5. If a pixel has multiple changes for three dates of assessment (i.e. from LU1 to LU2 and to LU3), it is regarded as fuzzy state. Even though a possibility of the multiple changes may be true, but it may also be caused by the error of the

classification images. Therefore, it is regarded as "fuzzy". This rule was applied by excluding the irreversible change as mentioned in rule 3.

4.3.6. Land use change analysis and land use change trajectories

Land use change analysis was conducted by using post classification change comparison method. Post classification was regarded as the most accurate procedure and presented the nature of changes (Mas, 1999). Main advantage of post classification is it includes: detailed from-to information. It eliminates the difficulties at analyzing of images at different period of time and even different censors (Mas, 1999).

Land use change trajectories were assessed by applying cross tabulation of the sequence maps of land use 1994, 2002 and 2014 from the result of the images classifications. Each land use class was represented by a number: 1 = Agro-forestry, 2 = Settlements/Infrastructures, 3 = Vegetable croplands, 4 = Plantation forest, 5 = Paddy field, 6 = Plantation, 7 = Shrub rangeland. And the land use trajectories were the shift of the land use classes from 1994 to 2014 symbolized by the number. For example, "1,3,3" means that Agro-forestry in 1994 changed into vegetable croplands in 2002 and remained vegetable croplands in 2014.

4.4. Soil erosion analysis

Soil erosion analysis was conducted by applying steps and involving data as described by Figure 4.5.



Figure 4.5. Soil erosion analysis steps and data

4.4.1. Input layers

Since the annual soil loss assessment of Watem/Sedem was based on RUSLE (Renard et al., 1997), the data in this analysis refers to RUSLE input data layers as described by this formula:

 $E = RxLS_{2D}xKxCxP \text{ (van Oost et al., 2000; van Rompaey et al., 2001)}$ E = annual soil erosion R = rainfall erosivity K = soil erodibility C = crop factor management P = erosion control practice $LS_{2D} = \text{two dimensional topography factor}$

The assessment of the mean annual transport capacity was calculated using formula below:

 $TC = KTc * R * K * (LS_{2D} - 4.1s^{0.8})$ (van Rompaey et al., 2001; Schmengler, 2010;) s = slope gradient

All input layers were generated in Idrisi32 with a resolution of 20x20m. The resolution of 20x20m was applied because the Watem/Sedem model was calibrated with resolution 20x20m (van Rompaey et al., 2001). The input layer consisted of rainfall erosivity (R factor), soil erodibility (K factor), topography (LS factor), crop cover (C factor), and Parcel map. P factor was considered to be 1 in the Watem/Sedem model because the conservation practices are mostly in small scales that cannot be detected by Landsat satellite images.

1. Erosivity factor (R),

Rainfall erosivity (R factor) refers to the result of multiplication between storm energy (E) and the the maximum rainfall intensities in 30 minutes (I). Since the detail data required by RUSLE is not available, the R factor was calculated by using a formula proposed by Bols, (1978) who did a research in Indonesia relating to erosivity (R) to annual precipitation (mm/year).

$$R = \frac{2.5P^2}{100(0.073P + 0.73)}$$
(Bols, 1978)

P = Annual precipitation (mm)

Since the input layer for rainfall erosivity in the Watem/Sedem model must be in MJ mm $m^{-2} h^{-1} year^{-1}$, the Erosivity was divided by 10,000. Then the R value for each rainfall station was interpolated by using Inverse Distance Weight (IDW) with power 3 to produce the erosivity map. Power 3 was selected by considering a more appropriate result of the interpolation.

Considering the high variation of spatial distribution of rainfall in Merawu watershed, and because only single value of erosivity that could be inputted into the Watem/Sedem model, the erosivity map was multiplied with erodibility map and the value for erosivity was given 1 in the Watem/Sedem.

2. Erodibility (K), was calculated by using formula proposed by (Declercq & Poesen, 1992):

 $K = 3.5 + 38.8 * exp(-0.5((logDg + 1.519)/0.7584)^{2})$

Dg = Geometric mean particle diameter K = Soil erodibility (kg h MJ⁻¹mm⁻¹)

 $Dg (mm) = Exp(0.01 \sum fi \ln mi)$ (Renard et al., 1997)

fi = the primary particle size fraction in percent m = the arithmetic mean of the particle size limit (Shirazi & Boersma, 1984).

The arithmetic means of particle size limit were 0.001 mm for clay, 0.026 mm for silt, and 1.025 mm for sand (Shirazi & Boersma, 1984). The soil erodibility was calculated for every soil data and then it was mapped based on geomorphological unit.

3. Crop management Factor (C factor) Map.

Crop management factor was determined by using vegetation indices approach proposed by (Sulistyo, 2011b) who conducted a research in Merawu watershed in 2011.The following formula was used to derive C factor:

C = 0.60 - 0.77 NDVI, (Sulistyo, 2011b)

The value of C factor ranged from 0 - 1 (Schmengler, 2010). The result of the calculation ranged from "< 0 to 1". Therefore, all value ≤ 0 was considered to be 0.001. It was the lowest C factor value and attributed to dense forest. And C factor was not grouped into classes. Each pixel represented its own value. It was meant to prevent the effect of generalization in each class of reclassification.

4. Topographical map or LS factor was generated from DEM (Digital Elevation Model). It was internally produced by Watem/Sedem model. The DEM was derived from contour lines interpolation. To accommodate RUSLE to a two dimensional landscape, the slope length (L) was derived by applying formula:

$$L_{i,j} = \frac{(A_{i,j} + D^2)^{m+1} - A_{i,j}^{m+1}}{D^{m+2} X_{i,j}^m (22.13)^m}$$
(Desmet & Govers, 1996)

L = the slope length, *A* = the unit contributing area, *D* = the grid cell length (m), $X_{i,j} = \sin a_{i,j} + \cos a_{i,j}$, $a_{i,j} =$ aspect direction for the grid cell with coordinates, *m* = the slope length exponent.

5. Parcel map

Parcel map was created from reclassified land use maps. Each land use was given new identity:

10,000 = forest,
20,000 = shrub
100, 200, 300, 400 = fields under agriculture
-2 = roads and infrastructure
-1 = river
0 = out of the study area

This map was created by utilizing overlay function in GIS software. Parcel map was needed to take into account the effect of land use borders and other infrastructures such as roads to the probability of sedimentation.

4.4.2. Model calibration

Model calibrations aims to increase the model performance by adjusting certain model parameter and comparing it to the field data in order to get a prediction that matches the observed value (Morgan, 2011). The values to be assigned in the calibration must be in a range of those observed in the field or laboratory (Morgan, 2011).

The Watem/Sedem model calibration was conducted by adjusting the Transport Capacity coefficient for different land use types. It then was compared with sediment record from PT. Indonesia Power. Watem/Sedem provides two kinds of Transport Capacity coefficient (KTc) that could be adjusted to get the better result: KTc High and KTc Low. KTc high is for less vegetated areas and KTc low is for dense vegetated areas. To differentiate which part of the watershed that was supposed to be categorized to have low KTc or high KTc, Watem/Sedem provides C factor threshold which is called KTc limit as 0.1 (Notebaert et al., 2006). Area with C factor less than 0.1 is given KTc low and area with C factor more than 0.1 is given KTc high. The relativity of low KTc and High KTc was kept constant, and ratio 1:3.3 between KTc low and KTc high was applied following (Verstraeten, Poesen, Gillijns, & Govers, 2006).

The model calibration was conducted by using sediment data 2014. This data (2014 sediment data) was used because it is the only data that has complete supporting data to undertake the calibration (sediment and the Satellite image for C factor), while others (sediment data 2006 to 2013 had no satellite image to generate C factors).

4.5. Establishing Dynamic Tolerable Soil Loss spatial information (T values)

Tolerable soil loss assessment was conducted from the perspective of crop productivity. It was approached from the minimum soil depth needed by the farmers to gain optimum crop productivity. However, in this analysis tolerable soil loss was assessed not only based on soil depth but also involving annual soil erosion since soil erosion is an inevitable process that can cause addition or subtraction on soil depth. It corresponds with Stamey & Smith (1964) saying that tolerable soil loss must be adaptable with erosion and renewal rates of any soil characteristics. Consequently, what is called tolerable soil loss in this analysis was the amount of allowable soil loss after certain amount of annual soil erosion.

Tolerable soil loss was analyzed in two erosion periods or soil resources life time. The first was by following Morgan (2005) where soil loss is defined as the allowable soil loss that can maintain the soil fertility for 20 to 25 years. The second way was by applying Arsyad (1986) suggestion that the period of 400 years should be used to assess to tolerable soil loss, because this period was judged to be adequate to maintain soil sustainability. The two alternatives of tolerable soil loss assessment was meant to provide alternatives for stakeholders who have interests in land utilization in Merawu river basin depending on their ending points (Bui, Hancock, & Wilkinson, 2011)

A modification of formula by (Bui et al., 2011) was applied. The formula of Bui et al., (2011) was as following :

 $T = \left(\frac{\Delta S_{0.75}}{C}\right) + (Vsoil) + (D) \text{ (Bui et al., 2011)}$ T = Annual tolerable soil loss (mm/year) $\Delta S_{0.75} = \text{The thickness of soil from the crop yields drop below 75\% (mm)}$ Vsoil = Soil formation rate (mm) D = Deposition (mm) C = Soil resources lifetime (year)

The formula was modified by inserting soil erosion and deposition spatial distribution from the result of erosion simulation by Watem/Sedem model into the equation. The application of soil erosion map into the equation was to get tolerable soil loss that is dynamic toward annual soil erosion. The formula was modified as following:

Tx, y =	$= \frac{(Ed - d_{min})}{t_s} + (Exy) + (V_{soil})$, or (1)
<i>Tx</i> , <i>y</i>	$=\frac{(Ed-d_{min})}{t_s}+(Dxy)+(V_{soil}) \qquad (2$
Tx,y	= Annual tolerable soil loss in point x,y (mm)
Ex,y	= Annual soil erosion rate in point x,y (mm), (-)
Dx, y	= Annual deposition rate in point x,y (mm)

Ed = Maximum soil depth considered fertile (mm)

 d_{min} = Min soil depth needed for growing crop (mm)

 t_s = Proposed lifetime for using soil resource (year)

$$V_{soil}$$
 = Soil formation rate (mm year⁻¹)

First equation was used for all area where the value of erosion assessment (negative) which means soil loss occurred, and the second equation was used if deposition occurred (positive value). The erosion and deposition map was from the result of Watem/Sedem erosion modeling.

Soil depth information was retrieved from farmer's local knowledge through a set of interview that has been explained before. Soil erosion map was derived from the result of Watem/Sedem netto erosion map. Soil formation rate used single value (2.5 mm/year) for all the catchment areas from (Arsyad, 1989). Present soil erosion from the result of Watem/Sedem was assigned as the soil erosion rate during the erosion period.

4.6. The effect of soil loss on crop productivity

This analysis was dedicated to assess the relationship of the tolerable soil loss and soil loss on crop productivity. The analysis was aimed to find out whether the soil loss has affected crop productivity and to identify whether tolerable soil loss spatial information was confirmed by the crop productivity point of view. For that purpose a semi-structured interviewed with famers has been conducted in all watershed area.

43 samples have been collected that were distributed based on the morphology units. The interview was mainly aimed to dig information about the trend of crop productivity during the last 20 years. The interviewees were selected purposively in each sampling unit. A criteria have been determined that interviewees must be over 35 years, since most of the farmers have started to their work in their crop lands since they were 15 year old. It was hoped that the respondents experienced at least last 20 years of harvest.

The questions of the interview were designed as simple as possible. Beside digging information about the trend of crop productivity, farmers behavior of using fertilizers was also assessed to anticipate other factors that influence crop productivity such as fertilizers.

The main questions were:

- 1. What do the farmers think about the trend of crop productivity the last 20 or 15 years? Is it declining, increasing or remaining constant?
- 2. Do the farmers use fertilizers for their crops? Is the amount of fertilizers that they use for their crops increasing/declining/remaining constant the last 15 to 20 years?

5. RESULTS AND DISCUSSIONS

This chapter presents the result and discussion that were obtained from data analyses. The data analyses performed land use change analysis and land use change trajectory, dynamic soil erosion by applying Watem/Sedem erosion model, tolerable soil loss and the effect of soil loss on crop productivity.

5.1. Land use change analysis

The use of temporal image of satellite data in assessing land use change is an undisputable choice (Imhoff et al., 1997). Data from satellite image has been proven and demonstrated to be satisfactory in land use change assessment (Imhoff et al., 1997). The advantage of using satellite images is that satellite images offer repetitive coverage and consistent quality of images (Singh, 1984, 1989) which is important in detection land use change.

However, the use of temporal image data conceives sources of errors: geometry and radiometry (Richards & Jia, 1999). Therefore when an image is to be utilized, it is necessary to conduct geometry and radiometric correction attached in the image (Danoedoro, 2012) to establish direct linkage between the images and the biophysical phenomena, to remove image noise and data acquisition error because image noise will affect the change detection capabilities (Coppin et al., 2004).

In this research, geometry correction was not conducted because the correction has been undertaken by USGS as image's provider. Radiometric correction was carried out by converting image's Digital Number to at sensor radiance, and radiance value to Top of Atmospheric reflectance. In addition to remove noise and haze, Dark Subtraction (DOS) module by using ENVI 5.1 was undertaken. Hence, even though this research uses temporal image data that is potential to have errors, the error sources have been minimized. In addition, all of the images were in the same season: dry season. All of the pre processing steps were executed by using ENVI 5.1 software.

5.1.1. The result of image classifications

The spatial distribution of the land use of 2014 is showed by Figure 5.2. The result of the image classification 2014 shows that the dominant land use was agro-forestry (39.6% of the catchment) that mostly can be found in Pejawaran, Wanayasa, and Karangkobar sub districts. Vegetable croplands and plantation occupied 20% and 17% of the area respectively. Batur, Pejawaran and Wanayasa were where the vegetable croplands mostly could be found. And Madukara and Pagentan sub districts were

predominated by *Salacca zalacca* (salak) plantation. Pine forests (Plantation forests) and shrub rangelands dominated the upper part of the watershed border, while the southern part was dominated by paddy field such as in Banjarmangu sub district and some part of Madukara and Pagentan sub district. All of the three land uses occupied 23% of the catchment area. The result of images classifications 1994 and 2002 also show the same pattern as above. Merawu watershed in 1994 and 2002 was also dominated by agroforestry, vegetable croplands and plantation. The spatial distribution was also relatively the same as in 2014. The results of the classifications of image 1994 and 2002 are presented in Figure 5.3 and Figure 5.4, and Table 5.1

Land use	1994 (ha)	2002 (ha)	2014 (ha)
Agro-forestry	8,890	8,126	9,248
Settlements/Infrastructures	950	1,034	1,407
Vegetable cropland	5,810	5,466	4,776
Plantation forest	1,833	2,252	1,504
Paddy field	1,329	1,528	1,009
Plantation	3,175	3,554	4,037
Shrub rangeland	1,363	1,390	1,369

Table 5.1. Land use change tabulation from 1994 to 2014

Land use spatial distributions in Figure 5.2, Figure 5.3, Figure 5.4 show that Merawu watershed was highly influenced by agricultural activities. It is reflected by the positions of each land use types, especially the agricultural ones that are aimed to gain the optimum crop productivity. For instance, the location of vegetable croplands that are mostly in the steep slopes despite the bigger effort needed to carry seeds and fertilizers to the locations. It is to avoid the crops to be decayed by high rainfall intensities in the area. Because, steep slopes and high altitude enable run-off from rainfall to be directed to lower places quickly and not flooding the croplands area. That's also why the middle part of the catchment that is not too steep is planted by agro-forestry (cassava, maize, albasia, bamboo, etc) and plantation which are more resistible to water.

Agricultural activities that are prominent in Merawu watershed correspond with most land use patterns in most catchments in Java (Pawitan, 2004). Main rivers catchments in Java are dominated by agricultural land which are about 50% to 85% and forest cover is less than 20% of the catchment area (Pawitan, 2004). For instance, Ciliwung watershed, it is dominated by Agricultural area about 70% of the catchment. The dominant agricultural area is closely related with farmer's skill that still relies on extensive agricultural practice. In addition, population growth is not followed by adequate job opportunity growth (Dwiprabowo et al., 2012). Consequently, the dependence on agricultural lands becomes very high.







D









G Figure 5.1 Land use features

A= shrub rangeland, B= vegetable cropland, C= agro-forestry, D= paddy field, E=plantation forest, F= settlement/infrastructure, G= plantation



Figure 5.2. The result of image classification 2014



Figure 5.3. The result of image classification 2002



Figure 5.4. The result of image classification 1994

5.1.2. The accuracy assessment of image 2014 classification

Accuracy assessment of image classification is necessary to figure out how well the work of image classification is. This gives information to users how reliable the information of the result of image classification compared to ground data (Congalton, 2001). The accuracy assessment was conducted by applying ground data of land use as the references. The ground data were collected in the field and a part of them was from Google Earth image 2014. A part of the data was used as guides for determining training samples. The data used for training sample were separated from data used for accuracy assessment. The accuracy assessment was conducted by applying error matrix and Kappa statistic as explained in Chapter 4.

The result of the accuracy assessment of image classification on Landsat image 2014 shows that the overall accuracy up to 80.2% and Kappa coefficient 0.76. It means that 76% of image classification agreed with the reference data. Its strength of agreement is categorized as "substantial" or good (0.61 to 0.80) (Landis & Koch, 1977). And the producer's accuracy and user's accuracy of each class are showed by Table 5.2. Producer's accuracy represents the probability of the reference data that is correctly classified (Congalton, 2001). The user's accuracy reflects the probability of classified samples truly represents the ground reality or also called the reliability of the image classification (Congalton, 2001).

High user's accuracies were detected in shrub rangeland, plantation forest and settlement/infrastructures where the reliability was more than 90%. In contrary, the reliability of Agro-forestry is only 64%. High accuracy in shrub rangeland is caused by the location of shrub rangeland that is separated from other land use in the northern part of the watershed. Therefore the possibility of other land use types to be commissioned into shrub is very small even though the reflectance of the training samples in Figure 5.5 shows that it is close to plantation and agro-forestry. The same thing also occurred to plantation forest. Beside the location that is quite separated from other land use types, Figure 5.5 shows that the reflectance of plantation forest is quite distinctive from others. It contributes to the high reliability of plantation forest class. Meanwhile, the reflectance of settlements/infrastructures training sample is also distinctive from other classes.

Low accuracy in agro-forestry is caused by the confusion among Agro-forestry with other land use types due to there is not any exact separation in the field. Moreover, agro-forestry land use type has so many features due to the various plantation combinations from maize to albasia or bamboos with different densities of the vegetation covers. Consequently, the reflectance of agro-forestry overlapped with other land use types such as with plantation, vegetable croplands and shrub. The example of various features of agro-forestry is presented in Figure 5.6.



Figure 5.5. Statistics of Region of interest (training samples) used for image classification

Table 5.2. Accuracy	assessment tabulation
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		References							User's	Producer's
Predictions	1	2	3	4	5	6	7	Grand Total	accuracy (%)	accuracy (%)
Agro-forestry (1)	43	4	6	4	3	4	3	67	64	72
Settlements/infrastructures	3	64	1	1	1	1		71	90	85
(2)										
Vegetable croplands (3)	2	6	41		2		3	54	76	84
Plantation forest (4)				24			2	26	92	83
Paddy field (5)	4	1	1		21			27	78	78
Plantation (6)	7					20		27	74	80
Shrub rangeland(7)	1						30	31	97	79
Grand Total	60	75	49	29	27	25	38	303		



В



Figure 5.6. Various features of agro-forestry A) Agro-forestry dominated by cassava and albasia, B) Agro-forestry dominated by cassava and trees, C) Agro-forestry dominated by dense bamboo.

5.1.3. Land use change detection rationality evaluation

Change detection analysis by using temporal data series has several sources of error: location error and classification error (Carmel, Dean, & Flather, 2001). The classification error comes from incorrect assignment of land use class pixels to certain objects and the location error comes from the misregistration between several datasets (Carmel et al., 2001). And the one-time classification accuracy assessment applied in this study has potential of error propagation in change detection from the accumulation of error of various temporal data (Liu & Zhou, 2004). In addition, the effect of radiometric and atmospheric attenuation from the different time of data acquisition can reduce the accuracy of the observed change (Carmel et al., 2001). Since the one time classification accuracy assessment may propagate error in change detection (Liu & Zhou, 2004), the rationality of changes in temporal data becomes important to be undertaken.

The result of rationality evaluation in Table 5.3 shows that the correctly classified pixels based on Rule 1 (no changes detected) and Rule 2 (only one change detected) equaled to 48% and 33% respectively. Pixels in fuzzy state based on Rule 4 (the changes reverse back to the initial land use type) and Rule 5 (the land use changes in all dates) were 13% and 4% respectively. Meanwhile, the incorrect classified from the reverse changes from settlement/infrastructures to other land use types (rule 3) was 1.7%. Therefore, the correctly classified pixels is 81%, 17% is in fuzzy state and 1.7% was incorrect. After all, the overall accuracy of rationality of change detection was 81% (by ignoring the fuzzy pixels).

	Rules	Pixel numbers	%
Correct	Correct rule 1	144	48
	Correct rule 2	100	33
	Total	244	81
Incorrect	Rule 3	5	2
	Total	5	2
Fuzzy	Rule 4	40	13
	Rule 5	11	4
	Total	51	17
Total		300	100.00

Table 5.3. Overall rule-based rationality evaluation results

5.1.4. Land use change trajectories

Trajectories are trends over time that shapes the relation of factors that cause human environment change and their effects (Mertens & Lambin, 2000; D. Wang et al., 2013). Trajectories captures the similarities of land use change and use them to analyze the process regularities (D. Wang et al., 2013). Therefore, this sub-section is aimed to describe the path of dominant changes in order to be able to understand characteristics of land use change and possible factors of the changes in Merawu watershed.

During 1994 to 2014, Merawu watershed was dominated by agro-forestry, and followed by vegetable croplands and plantation. Meanwhile, settlement/infrastructure was the least land use type. Settlement/infrastructure and plantation had always increased steadily. It corresponds with the high rate of population growth in Banjarnegara which reaches 0.9% per year in average since 1994 to 2012 (BPS Banjarnegara, 2013). In contrary, vegetable croplands kept on decreasing. Meanwhile, other land use types had mix increase and decrease trends in 20 years, such as plantation forest that increased 22% from 1994 in 2002 and decreased 33% from 2002 to 2014. The increase of plantation forest from 1994 to 2002 reflected the efforts of reforestation undertaken by the government which is the annual program of the Government to reduce critical land (The Government of Banjarnegara District, 2013; The Public Relation of East Java Province, 2014). The overall result of land use change during 1994 to 2014 is showed by Table 5.1.

The cross tabulation of the sequence land use maps (1994, 2002, and 2014) shows there were 260 kinds of change trajectories (Appendix 4). Among them, 20 trajectories occupied more than 1% of total areas Table 5.4. The others were in small fractions (less than 1% of the areas). The largest trajectories were dominated by stable (unchanged) land uses during the three periods of time. The unchanged areas occupied

50% of the total catchment (Table 5.4). The unchanged land use occurred in the northern part for plantation forest and shrub (Batur and Wanayasa Sub Districts), agro-forestry and vegetable croplands were mostly in Kalibening, Wanayasa, Batur and Karangkobar. Plantation was mostly in Madukara and Banjarmangu Sub districts, and paddy field was mostly in Banjarmangu Sub district Figure 5.7.

Three dates of changes tabulation (by excluding the unchanged pixels) shows that the biggest changed occurred among agricultural land use types. It was dominated by dynamic changes from agro-forestry to vegetable croplands and vice versa (such as 3,1,1, 1,3,1, 3,3,1). The 20 largest trajectories can be checked in Table 5.4. The changes among the agricultural land use types are possible to happen in Merawu watershed since the agricultural fields belong to the people that were dynamically changed their crops depending on the weather, plants diseases and crop yields selling price in the markets. The trajectories distribution is presented in Figure 5.7.

No	1994	2002	2014	Area (Ha)	Trajectory ratio to total catchment area
1	1	1	1	4258	18.2%
2	3	3	3	2884	12.3%
3	6	6	6	1966	8.4%
4	3	1	1	1013	4.3%
5	5	5	5	705	3.0%
6	1	3	1	671	2.9%
7	7	7	7	643	2.7%
8	3	3	1	642	2.7%
9	3	1	3	632	2.7%
10	4	4	4	602	2.6%
11	1	6	6	581	2.5%
12	2	2	2	578	2.5%
13	1	1	6	504	2.2%
14	1	4	1	489	2.1%
15	1	1	3	396	1.7%
16	1	3	3	392	1.7%
17	1	6	1	307	1.3%
18	6	1	6	305	1.3%
19	1	4	4	292	1.2%
20	4	1	1	284	1.2%

Table 5.4. Land use change trajectories

1 = agro forestry, 2 = settlements/infrastructure, 3 = vegetable croplands, 4= plantation forest, 5 = paddy field, 6 = plantation, 7 = shrub rangeland.



Figure 5.7. Map of land use change trajectories 1994 to 2014

a. Land use change during period of 1994 to 2002

During 1994 to 2002, forested area conversion were dominated by agro-forestry (411 ha), vegetable croplands (174 ha), and shrub (404 ha). It marked that forest degradation during this period was dominantly due to the expansion of agricultural land

and abandoned land. Most of the forest conversion took place in areas with slope 15-30% and 30-70%, dominated by agro-forestry in Pejawaran and Wanayasa sub districts.

The conversion of non forested areas to forest is also noticeably identified. The most contributors of reforestation came from agro-forestry (981 ha), shrub rangeland 253 ha, and plantation (178 ha). It took place in areas with slope between 30-70% mostly in Wanayasa, Madukara and Karangkobar sub districts. The reforestation area can be checked in Appendix 20.

The conversion of forest to agricultural land use is a common pattern in Indonesia land use changes as some other studies have confirmed that the expansion of agricultural area has brought to deforestation (Dwiprabowo et al., 2012; Firdaus & Nakagoshi, 2013). Dwiprabowo et al., (2012) found that during 1990 to 2011, the area of plantation, settlement, and cropland in Papua and South Sumatera Province had increased and at the same time the area forests decreased. It was only in East Java that forest area had an increasing trend due to the increasing of people's interest in developing community forests. Meanwhile Firdaus & Nakagoshi (2013) reported that in Batang Merao watershed, Jambi in Sumatera island, during period of 2006 to 2011, most of the forests have changed into mix plantation and agricultural areas.

Changes among agricultural land use types occurred, such as such as paddy field changed into plantation, plantation to agro-forestry, and vegetable cropland, and vice versa. And the area of agro-forestry and vegetable cropland had the highest increasing rate among others (Appendix 5).

The changes among agricultural land uses are caused by the several reasons. Some of them are due to the possibility of gaining more profit, such as the introduction of potatoes that gives more profit and replaced tobaccos, or the introduction of new kinds of favorable plant in the market, like the massive planting of *Salacca zalacca* (salak) plantation that started 15 to 20 years ago, pest or diseases attacks on certain plants or crops, and weather fluctuation

b. Land use change during period of 2002 to 2014

During 2002 to 2014, the biggest land use shift took place between vegetable croplands to agro-forestry and followed by vegetable croplands to agro-forestry with almost the same amount of area (Appendix 6). The changes overlapped in almost the same slope zones. It mostly occurred in Wanayasa, Karangkobar and Pejawaran Sub districts. The largest conversion on vegetable croplands to agro-forestry was found in area between 7-15% and 15-30%, while agro-forestry to vegetable croplands area mostly took

place in area with slope between 15-30% and 30-70%. The land use change distribution based slope zones period 2002 to 2014 can be accessed in Appendix 7.

Noticing the changes between agro-forestry and vegetable croplands and slope zone of the changes, it can be inferred that the changes were related to landscape characteristics that was more appropriate for certain plants or crops. The land with slope 15-30% and 30-70% is ideal for vegetable croplands, especially potatoes. In areas where the rainfall intensity is high such as Merawu watershed, this type of slopes can deliver the run-off of quickly out of potatoes land (vegetable croplands) before it floods and decays the crops. On the other hand, lower slopes are disadvantages for vegetable croplands where the rainfall tends to stay in the field and can deteriorate the crops as vegetable croplands such potatoes required well drained soil (Zarka, Kells, Douches, & Buell, n.d.).

During this period, plantation forest conversion occurred larger than period of 1994 to 2002. The largest conversion occurred from plantation forest to agro-forestry area, followed by plantation and shrub. All of the shifts took place mostly in areas with slope between 30-70%. It mostly occurred in Wanayasa and Karangkobar Sub districts. It can be checked in Appendix 20. Meanwhile, the largest land use type conversion to forest came from shrub rangeland. It took place in areas with slope in range of 30-70% which were mainly in Batur, Wanayasa, and Kalibening Sub districts.

The forest conversion is suspected to be related with post monetary crisis phenomena during 1997 to 1998. After the crisis, so many people's businesses in urban were collapse. Consequently, many people who lived in urban area came back to their villages and started to be farmers again (Rustanto, 2010). Therefore, the need of land increased and forest conversion occurred.

Paddy field continued to sink and changed mostly to agro-forestry and plantation. People in Merawu watershed found that paddy field was no longer beneficial compared to *Salacca zalacca* (Salak). The harvest yield of Salak is more promising in the market price, and for that reason the conversion of paddy field to plantation occurs massively in Madukara, and Pagentan Sub districts. While the plantation and shrubs mostly shifted to agro-forestry in area between 15-30% and 30-70% in Kalibening, Pagentan and Karangkobar sub districts.

Focusing on agricultural land use types (vegetable croplands, agrofroestry and plantation) and the plantation forest, during 1994 to 2002, the number of agricultural land uses (vegetable cropland, agro-forestry, and plantation) decreased about 700 ha or 4% in 2002 compared to 1994. Meanwhile the number of plantation forest increased about 412 ha or 22% in 2002 compared to 1994.

In period of 2002 to 2014, plantation forest declined drastically as much as about 750 ha or 33 %. The change mostly occurred in Batur, Wanayasa and Karangkobar. Forest conversion in Batur was dominated by the changes into shrub, and the forest conversion in Wanayasa and Karangkobar was mostly into agro-forestry.

The agricultural land use types (vegetable croplands, agro-forestry and plantation) increased in total 915 ha in 2014 compared to 2002. However, not all of them showed positive trend. In contrary to the other two land uses (agro-forestry and plantation), vegetable croplands decrease 807 ha or equals to 15% of the initial areas in 2002. Agro-forestry and plantation increased 10% and 13% respectively.

The conversion of non forests to forests is an uncommon phenomenon in Indonesia, unlike the conversion of forests to non forests (Pawitan, 2004). But since the forest area in Merawu watershed is plantation forest (Pine forests) and belongs to the Government, the reforestation is possible to happen as explained previously. In addition, the reforestation can also happen due to the increase of the number of community forests (Dwiprabowo et al., 2012).

5.2. Soil erosion analysis

5.2.1. Input data

5.2.1.1. Rainfall erosivity (R)

Rainfall erosivity is one of the dynamic parameters in Watem/Sedem erosion model beside C factor. Rainfall erosivity equals to storm energy (E) multiplied with rainfall intensities (every 30 minutes) (Wischmeier & Smith, 1978). It infers the potential erosion risk in a certain region where the slope is more than 9% (F.A.O, n.d.). Therefore, In RUSLE, the relation of EI parameter with soil loss is regarded linear (Renard et al., 1997).

This research used formula from the result of erosivity modeling from previous research conducted by (Bols, 1978) who mapped rainfall erosivity in Java and Madura Islands. This formula was used because deriving rainfall erosivity based on (Wischmeier & Smith, 1978) is not always possible due to the unavailability of data. Wischmeier & Smith (1978) required detail rainfall measurement (rainfall intensity in every 30 minutes). On the other hand, most Indonesia rainfall records are daily records that are recorded manually by operators. Hence, it is really difficult to get detailed rainfall record (at least 30 minute measurement) for such minimum 10 years of measurement.

The result of Erosivity calculation shows that rainfall erosivity ranged from 0.09 to 0.14 MJ mm/ ha year. However, the distribution of the rainfall erosivity varied in three

periods of erosion assessment (1994, 2002 and 2014). In 2002, erosivity in southern part of the watershed (Madukara, Pagentan, and Banjarmangu sub district) was higher than northern part (Kalibening, Wanayasa, Pejawaran, Batur and Karangkobar) as showed by Appendix 10. In 2014, erosivity in Batur and Pejawaran was detected as the highest and the lowest is in Wanayasa, Karangkobar and Banjarmangu appeared to be the lowest erosivity value (Appendix 9). Whereas in 1994, erosivity value was distributed more evenly (Appendix 11). However, the lowest value was still in Batur and Pejawaran, and the highest was in Banjarmangu.

However, at least, there were two limitations in the erosivity input data that may affect the accuracy of the soil erosion simulation. First, the number of the rainfall stations which were used was not the same for all assessment periods due to the limitation of data. In 2014, 7 rainfall stations were used. In 2002 and 1994, less rainfall stations were applied. Second, all of rainfall data except from Kalilunjar rainfall station were daily data that were recorded manually by hand writings of operators and sent each other among the operators (sub district to district level) manually and recopied manually. Consequently, the possibility of error due to human carelessness was quite high.

5.2.1.2. Soil erodibility (K)

Soil erodibilty is the sensitivity of soil toward soil erosion which is determined by physical and chemical properties of the soil (Arsyad, 1989) such as organic matter content, soil structure class, permeability, and the primary particle size fraction (Renard et al., 1997). Soil with high erodibilty is susceptible on the effect of rain drop and run-off.

Soil erodibility can also be approached only by using soil texture properties (soil texture fraction, geometric mean diameter, and the arithmetic mean of the particle size fraction) as also suggested by Renard et al.,(1997). Some research (van Oost et al., 2002; van Rompaey et al., 2001) have applied the use of soil texture properties in determining soil erodibility as also used in this research. It was claimed to give better result than the use of the original nomograph (van Oost et al., 2002). For that reason this research applied this method to derive soil erodibility.

The result of erodibility calculation shows that the soil erodibility value in Merawu river basin ranged from 16 to 42 Kg ha/MJ mm (Appendix 15). The dominant K values ranged from 30 to 42 which were classified as moderate to moderately high (Arsyad, 1989). Soil with this kind of erodibility values were moderately susceptible to soil detachment and also produces moderate run-off.

5.2.1.3. Crop management factor (C)

Vegetation cover plays important role in land management practices, soil erodibility and resistance to erosion (Schmengler, 2010). Good vegetation cover will reduce the effect of rainfall and topography on erosion (Arsyad, 1989). At least, there are 4 effects of vegetation cover on run-off and erosion: 1) rainfall interception, 2) slowing down run-off, 3) root's effect on soil structure stability and porosity, and 4) transpiration that reduce the soil moisture content (Arsyad, 1989).

Vegetation cover or C factor in this research was approached from the use of vegetation indices (NDVI). This formula was proposed by (Sulistyo, 2011b) who conducted a research in Merawu watershed by applying formula of RUSLE (Renard et al., 1997). The use of vegetation indices in determining C factor has also been applied by some other studies, such as (van der Knijff et al., 2000) who applied AVHRR image to derive the NDVI and (Alkharabsheh et al., 2013) who used NDVI from Landsat TM and ETM image to derive C factor.

The value of C factor in Merawu watershed ranged from 0.001 to 0.59 in 2014, 0.001 to 0.7 in 2002, 0.001 to 0.57 in 1994. High C value was detected in area which was intensively used for vegetables agriculture, such as in Batur District, Pejawaran and Wanayasa (Appendix 12, Appendix 13, and Appendix 14). From those figures, it was also figured out that high C factor in 1994 was detected larger than 2002 and 2014's condition. It means that 1994's vegetation cover was thinner compared to 2002 and 2014.

5.2.1.4. Topography factor (LS)

Topography factor in Watem/Sedem erosion model applied formula proposed by (Desmet & Govers, 1996) that modified the LS formula in RUSLE to two-dimensional terrain by using concept of unit contributing area on the "slope length". The work of (Desmet & Govers, 1996) takes into account the effect of slope irregularity on soil erosion instead of uniform slope in RUSLE. The uniform slope method always underestimates the slope risk due to the absence of the effect of slope convergence (Desmet & Govers, 1996). In addition, the use of uniform slope in RUSLE cannot predict the possibility of deposition location (van Oost et al., 2000).

Merawu River basin was dominated by slope range 15% to 30% (moderately steep) by 37% of the area that was distributed in all over Merawu catchment area, and following by slope range 30% to 70% (steep) as showed by Table 5.5 and Appendix 19. The "steep" slope was also spread in all sub districts, especially in Batur, Pejawaran, Karangkobar, and Wanayasa. 4% of the catchment was in slope of 70% to 140% (very steep) and >140% (extremely steep). They were located in upper part of the slopes in sub

districts such as Batur, Wanayasa, Karangkobar, Madukara, Pagentan, and Banjarmangu. But, mostly, they were found in Wanayasa sub district. Dominant steep slope in Merawu catchment causes run-off velocity is accelerated and becomes more erosive.

Slope (%)	Slope class	Area (%)
0-2	Flat or almost flat	2.2
2-7	Gently sloping	7.5
7 – 15	Sloping	15.9
15 - 30	Moderately steep	36.8
30 - 70	Steep	33.6
70 - 140	Very steep	3.5
>140%	Extremely steep.	0.6

Table 5.5. Slope class and the area coverage in percent

5.2.1.5. Conservation practice (P) factor

Conservation practice in Watem/Sedem model is regarded as "1" since it is very difficult to recognize the P factor through Satellite images due to its small size of practice in the field.

5.2.2. The Watem/Sedem calibration

The Transport Capacity coefficients were assessed, starting from the model's default value 75 m and 250 m and by considering some limitation as explained above. The result of model calibration is shown by Table 5.6.

Transport	Sediment		Ratio of Model	
Capacity	Export from	Field	Results and	Voor
Coefficient	Watem/Sedem	measurements (m ³)	Field	I Cal
(KTc) (m)	(m^3)		Measurements	
Ktc 75 and 250	981,361.48	1,440,537.34	0.80	2014
Ktc 80 and 264	998,655.56	1,440,537.34	0.82	2014
Ktc 90 and 297	1,032,525.2	1,440,537.3	0.84	2014

Table 5.6 The result of the Watem/Sedem model calibration

The table showed that the most optimum Transport Capacity coefficient was KTc 90 m and 297 m. It was showed by the ratio of model simulation results and field measurements that is closer to 1 compared to two others. The column of "ratio" described how fit the model describes the field sediment data.

The calibration result showed that the model result underestimated the soil erosion if compared to field measurements. The underestimation could be understood as the consequence of the inability of Watem/Sedem model to take into account the extreme events such as landslide and stream banks erosion that frequently occurred in Merawu watershed. However, KTc 90 m and 297 m gave 0.84 of fitness between the Watem/Sedem model result and the field measurement. It is considered to be quite good to use to model soil erosion in Merawu watershed. Therefore Transport Capacity coefficient 90 m and 297 m was used for erosion assessment in 2002, 1994 and 2014.

5.2.3. The erosion modeling result

Soil erosion analysis simulated by Watem/Sedem resulted in the magnitude of soil erosion and deposition. It resulted in spatial variability of soil erosion and deposition that occurred in Merawu watershed. The summary of the result is presented in Table 5.7. The Watem/Sedem model also produced spatial distribution of soil erosion and deposition as presented in Figure 5.14, Figure 5.15, and Figure 5.16

Watem Sedem output	1994 (ton/year)	2002 (Ton/year)	2014 (Ton/year)
Total sediment production	11,095,562	3,443,927	3,954,866
Total sediment deposition	8,076,980	2,214,243	2,606,681
Total sediment export	3,018,582	1,229,729	1,348,185
Total River export	3.018,125	1,229,177	1,347,436

Table 5.7. Summary of the Watem/Sedem model results

The output of the Watem/Sedem as in Table 5.7 can be explained as following (Notebaert et al., 2006):

- 1. Total sediment production is the sum of net soil loss for the whole study area.
- 2. Total sediment deposition is the sum of net deposition in whole study area.
- 3. Total sediment export is the amount of sediment production minus sediment deposition. It is the amount of sediment leaving the study area through river/channel/flow and other options.
- 4. Total river export is the amount of sediment leaving the catchment through only by river/channel and flow.

Watem/Sedem erosion model considers both pond deposition and sediment export. It reflects the amount of sediment transported through a river channel to a point or dam or outlet (Schmengler, 2010). But, in this research, it was assumed that there is no pond exists in Merawu watershed. Therefore there was no pond deposition. The sediment export was only the sediment that reaches the outlet. In addition, Watem/Sedem does not take into account channel/stream deposition. When the sediment reaches river/stream/channel, it is assumed that all sediment is transported to the outlet. The example of sediment transported through river channel in Merawu watershed is showed by Figure 5.8.



Figure 5.8. Sediment channeled through river in Banjarmangu Sub district

Table 5.7 shows that the ratio of deposition and sediment production in 2002 and 2014 was relatively the same (64% and 65% of the sediment production). A higher deposition was detected in 1994 which was about 73% of the detached soil particles was deposited in the field. Soil deposition represents the amount of soil accumulation within the catchment. By the fact of high total deposition, it means that the mobilization of soil due to soil erosion is very high. It indicates that the top soil has been transported somewhere else in the area of Merawu watershed from its initial position.

The high accumulation of soil deposition can be attributed to factors such as: topography, erodibility, erosivity and tillage. High deposition starts from high soil detachment within the catchment. High slope gradient that is dominant in Merawu watershed, high erosivity, quite high soil erodibility and intensive tillage practice by farmers has led to high soil detachment. On steep slopes, the sediment delivery of the detached material is energized by stronger Transport Capacity. However, it changes when the slope changes abruptly from steep slope to almost flat terrain as show by Appendix 22. The transport capacity losses its energy from high Transport capacity in steep slope to low capacity in almost flat terrain, and deposition occurred in large number before it can reach the rivers (Schmengler, 2010).

The major effect of agricultural practices on soil erosion is highlighted by Govers et al.,(1994). Govers et al.,(1994) said that intensive agricultural practice has caused additional erosion. Tillage activities redistribute soil in the field, consequently, in sloping land, soil deposition occurs in upslope side of field boundary and the soil erosion occurs in the downslope part, creating soil bank (Govers et al., 1994). One tillage operation (mouldboard-plough) is said to be responsible for erosion and deposition rate up to10 ton/ha/year in irregular landscape (Govers et al., 1994). In addition soil dispersions by

tillage also inter-mix the upper horizons, and it creates abrupt change with lower horizon since lower horizon is not affected by tillage. Therefore, the combination of tillage erosion is more important than just water erosion in many hilly areas Govers et al.,(1994). Even, tillage was suggested to be considered as a soil degradation process rather than something that makes soil sensitive to erosion (Govers et al., 1994).

Table 5.7 also shows that a great decline of sediment production and sediment export occurred from 1994 to 2002. Then the trend rose again in 2014. It corresponded with the land use composition, where in 1994, agricultural land use types which were the potential sources of soil erosion, especially the vegetable croplands, were larger than in 2002. Consequently, it caused soil erosion in 1994 higher than in 2002. If compared with land use composition of 2014, even though agricultural land use types of 2014 was larger than 1994, the area of vegetable croplands of 2014 was significantly less than 1994 (-1034 ha). Thus, it triggered higher soil erosion in 1994 than in 2014. The composition of land use (year 1994, 2002, and 2014) is presented in Figure 5.9.



Figure 5.9. Diagram of land use dynamic

The reason of high soil erosion in 1994 can also be explained by the value of C factors of 1994, 2002 and 2014. The histograms (Figure 5.10, Figure 5.11, Figure 5.12) show that mean values of C factor of 1994, 2002, and 2014 are 0.20, 0.07, 0.08 respectively. The mean of C factor value 1994 is much higher than those in 2002 and 2014. The lower C factor means the denser the vegetation, and the higher C factor means the thinner the vegetation cover. Therefore, it makes sense that the amount of soil erosion in 1994 was much higher than those in 2002 and 2014 due to the thin vegetation.



mean: 0.08 std. deviation: 0.09

Info Input: Output: Count Out: Count In:

0

The range of the soil loss and deposition value in both years was very high. Soil erosion ranged from 0 to 536,500 ton per ha and the deposition value reached the highest value as much as 541,400 ton per ha. Some pixels of erosion map produced by Watem/Sedem are detected to have very high soil erosion rates. The extreme values of soil erosion can be explained as the effect of rough terrain of Merawu watershed where steep slope gradient causes high value of soil loss and the abrupt change of terrain from steep slope to flat area accumulated the soil loss (Schmengler, 2010). However these extreme values of soil erosion in those pixels are only in very small size and scattered in the study area.

Figure 5.12. The histogram of C factor 2014

0

As a comparison of this research, Jatiningtyas (2012) has also conducted erosion analysis in Merawu watershed by performing RMMF erosion model in period of 2001, 2006 and 2010. The result of the RMMF model showed that the highest soil erosion occurred in 2002 (224,91 ton/ha/year), and the lowest was in 2006 (96,54 ton/ha/year). Meanwhile, the erosion rate in 2010 was (148,89 ton/ha/year). Compared to the observed sediment, these results overestimated the soil erosion. The spatial distribution showed that the highest erosion occurred in the middle part of the watershed that was occupied with vegetable croplands. On contrary, the upper stream part and downstream part showed lower erosion rate. The spatial distribution by Jatiningtyas (2012) showed similar pattern with the result of this research.

5.2.4. The Watem/Sedem model validation

Model validation is needed to test the accuracy of model prediction. It was undertaken by comparing the model results with field measurements data. For this purpose, sediment data from 2006 to 2013 was used to execute the model validation. However, the satellite data for the years of 2006 to 2013 to generate C factors were not available. Consequently, C factor of 2002 and 2014 were applied by assuming that C factors of 2002 was still relevant for 2006 to 2008 condition and C factor of 2014 was relevant for 2009 to 2013 condition.

Model validation was conducted by applying Coefficient efficiency by (Nash & Sutcliffe, 1970; Wang et al., 2015) and the coefficient of determination R². The sediment data from Watem/Sedem and the from field measurement are presented in Table 5.8.

Sediment Export from Watem/Sedem (m ³)	Field measurements (m ³)	Year
1,068,559.3	1,019,353.2	2013
900,245.2	1,527,128.5	2012
1,066,775.6	1,597,156.1	2011
1,515,590.4	2,375,196.1	2010
901,545.2	1,465,450.1	2009
1,048,374.8	1,259,626.8	2008
1,052,803	1,238,612.8	2007
848,617	1,259,257.4	2006

Table 5.8 Sediment data from Model prediction and field observation

1. Efficiency coefficient

Efficiency coefficient is statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Moriasi & Arnold, 2007).

Efficiency coeffcient = $1 - \frac{{\delta_i}^2}{{\delta_{obs}}^2}$ (Nash & Sutcliffe, 1970; Wang et al., 2015).
δ_i = variance of the residual between measured and the result of model δ_{obs} = variance of the observation sediment

The result of coefficient accuracy gave 0.75. The value of coefficient efficiency that is more than 0.5 means that the model is acceptable (Morgan, 2005). The value of 0.75 describes how well the observed data fits the model in 1:1 line (Moriasi & Arnold, 2007).

2. Coefficient of determination

Coefficient of determination describes the proportion of the measured data explained by the model (Moriasi & Arnold, 2007).



Figure 5.13. The relationship of simulated sediment with measured sediment

Figure 5.13 shows that R^2 value is 0.56. It means that the model can explain the measured sediment as much as 56%.

5.2.5. Spatial distribution of soil erosion and deposition

Table 5.9 presents that soil erosion affected 98% of the study area in 2014 and 99% in 2002 and 98.3% in 1994. It was only 1% to 2% of the catchment area that experienced deposition. The spatial distribution of soil erosion and deposition is presented in Figure 5.14, Figure 5.15, Figure 5.16. The figures show that Batur, Pejawaran, Wanayasa, Karangkobar, and Pagentan and Madukara were the sub districts that experienced worse erosion than others. The presence of steep slopes and intensive agriculture in the areas had caused severe erosion whenever the rain came.

Deposition occurred in smaller coverage of the catchment area compared to soil erosion even though the total amount of deposition reached up to 73% of the total sediment production. In other words, more than a half of the sediment production was deposited in study area. With coverage only less than 2% of the study area, it can be concluded that whenever deposition happens, the effect can be very severe (Schmengler,

2010) as deposition can cause crusting (Morgan, 2005). The crusting decreases the infiltration capacity from 45 to 60 mm/h to about 6 to 1 mm/h (Morgan, 2005). Therefore, areas in the steep slopes may have better infiltration rate due to less deposition (Morgan, 2005). Deposition in a large amount can bury the crops and the sedimentation of poor material over good material (Zachar, 1982).

Year	1994 (ha)	2002 (ha)	2014 (ha)
Erosion	22,961.6	23,065	22,928
Deposition	386.8	284	422

Table 5.9. Composition of erosion and deposition coverage area

Deposition distribution was scattered in all sub districts, such as, in the northern part, it was in Batur, Wanayasa and Pejawaran, and in the southern part of the watershed where the topography is relatively flat and almost flat, it was in Banjarmangu Sub district and where paddy field existed as sediment trapped. Parts of deposition distribution can be checked in Appendix 21 and Appendix 22.

In the northern part of the watershed (Batur, Wanayasa, Pejawaran) where vegetable croplands and agro-forestry were very dominant as the source of severe erosion, high deposition rate appeared. It happened because the possibility of soil particles exceeded the energy of the transport capacity is high. Consequently, deposition occurs when the transport capacity is less than the detached soil particles and when sufficient energy is no longer available to transport the soil (Morgan, 2005; van Rompaey et al., 2001). Moreover, in intensive agricultural landscape, the substances used in crop nutrients and pesticides are adsorbed onto the soil particles (Steegen et al., 2001). In addition the surface roughness of agro-forestry areas that are formed from mixed vegetation tended to prohibit the soil particle to be transported to the outlet and made the transport capacity ran out of energy immediately. That made vegetable cropland and agro-forestry as the sites where deposition mostly occurred.

About 56% (in 1994), 70% (2002) and 89.5% (1994) of the deposition area were dominated by deposition in range of 100 to 500 ton/ha and > 500 ton/ha (Table 5.10). Such high deposition rates occurred dominantly in Wanayasa, Pejawaran and Batur for condition of 2002 and 2014, and plus hilly parts of Karangkobar and Pagentan Sub districts in 1994. The deposition mostly occurred in concavities of agricultural area (Appendix 21). And the most prominent deposition location was in vegetable croplands, in northern part of Merawu watershed where convexities and concavities looked very distinctive. It corresponds with van Oost et al., 2000), saying that the soil erosion due to

tillage occurs in convexities and soil deposition in concavities. Soil deposition due to tillage reaches up to 100 ton/ha.year in average (van Oost et al., 2000). Soil accumulation was also noticeable in large coverage area in flat areas, such as in Banjarmangu sub district, in paddy field (southern part of the catchment), and in a plateau in middle part of Wanayasa sub district where abrupt change of slope occurs.

Deposition	Deposition	Cov	the	
rate(ton/ha/year)	classes	depos	ition aff	ected
		6	area (%)	
		1994	2002	2014
0 to 2	Very slight	1.29	2.47	1.11
2 to 5	Slight	0.94	1.19	1.23
5 to 10	Moderate	1.09	1.44	1.86
10 to 50	High	4.17	5.87	9.28
50 to 100	Severe	3.04	4.12	6.90
100 to 500	Very severe	11.85	15.48	23.71
>500	Catasthrope	77.62	69.43	55.91

Table 5.10. The deposition classification following Morgan, (2005)

Following the erosion classification based on Morgan (2005), the soil erosion tabulation is shown in Table 5.11. Table 5.11 shows that in 1994, 15.2% of the affected erosion areas experienced erosion in "catastrophic" category. Catastrophic erosion category is described as erosion rate that is indicated by extensive rills and gullies and the removal of most soil surface (Morgan 2005). In 2002, only about 6% of the erosion affected area experienced erosion rate in "catastrophic" category. Meanwhile in 2014, it was less than 2% of the affected erosion area that suffered from erosion of "catastrophic category". The spatial distribution showed by Figure 5.14, Figure 5.15, and Figure 5.16. In 2002 and 2014 condition the spatial distribution of erosion looked similar. Batur, Pejawaran and northern part of Wanayasa were the areas that experienced the "catastrophic" class of soil erosion. Vegetable croplands and agro-forestry in the steep slopes were the source of this rate of erosion. However, a different pattern was shown by the condition of 1994. Beside the aforementioned locations, Hilly parts of Karangkobar and Southern part of Wanayasa Sub District also experienced such erosion class. This happened due to the absence of forests in these areas as they existed in land use 2002 and 2014 (Appendix 20). Overall, most of the area of Merawu watershed was suffering from "high" to "catastrophic" erosion classes which is total almost 62% to 68% (2014 and 2002) and 89.5% (1994) of the watershed.

Erosion	Erosion	Coverage of the erosion							
rate(ton/ha/year)	classes	affe	cted area (%	6)					
		1994	2002	2014					
> -500	Catastrophic	15.20	5.7	1.91					
-100 to -500	Very severe	42.43	20.8	13.56					
-50 to -100	Severe	16.66	13.9	12.91					
-10 to -50	High	17.59	28.0	33.29					
-5 to -10	Moderate	2.64	7.8	9.79					
-2 to -5	Slight	1.67	8.3	9.27					
0 to -2	Very Slight	3.81	14.3	19.28					

Table 5.11. Soil erosion classification based on Morgan (2005)

Table 5.12 gives description how bad the erosion hazard in each class category. By large coverage of soil erosion in "high to catastrophic category", Merawu catchment is threatened by the potential existence of severe rills and gullies erosion. The erosion can remove most of the soil surface, creates sedimentation in the downstream and the crusting over large areas in the field (Morgan, 2005).

Code	Class	Erosion	Indicators
		rate (ton/ha)	
1.	Very slight	0 to 2	No evidence of compaction or crusting of the soil; no wash marks or scour features; no splash pedestals or exposure of tree roots; over 70% plant cover (ground and canopy).
2.	Slight	2 to 5	Some crusting of soil surface; localized wash but no or minor scouring; rills every 50–100m; small splash pedestals, 1–5mm depth, where stones or exposed trees protect underlying soil, occupying not more than 10% of the area; soil level slightly higher on upslope or windward sides of plants and boulders; 30–70% plant cover.
3.	Moderate	5 to 10	Wash marks; discontinuous rills spaced every 20– 50m; splash pedestals and exposed tree roots mark level of former surface, soil mounds protected by vegetation, all to depths of 5–10mm and occupying not more than 10% of the area; slight to moderate surface crusting; 30–70% plant cover; slight risk of pollution problems downstream if slopes discharge straight into water courses
4.	High	10 to 50	Connected and continuous network of rills every 5 -10 m or gullies spaced every 50–100m; tree root exposure, splash pedestals and soil mounds to

Table 5.12. Soil erosion classes and the indicators

			depths of 10–50mm occupying not more than 10% of the area; crusting of the surface over large areas; less than 30% plant cover; danger of pollution and sedimentation problems downstream
5.	Severe	50 to 100	Continuous network of rills every 2–5m or gullies every 20m; tree root exposure, splash pedestals and soil mounds to depths of 50–100 mm covering more than 10% of the area; splays of coarse material; bare soil; siltation of water bodies; damage to roads by erosion and sedimentation.
6.	Very severe	100 to 500	Continuous network of channels with gullies every 5–10m; surrounding soil heavily crusted; severe siltation, pollution and eutrophication problems; bare soil.
7.	Catastrophic	>500	Extensive network of rills and gullies; large gullies (>100m2) every 20m; most of original soil surface removed; severe damage from erosion and sedimentation on-site and downstream.

Source: Morgan (2005)



Figure 5.14. Map of netto water erosion 1994 in ton/ha/year.

Negative values indicate soil erosion occurrence and positive values indicate deposition



Figure 5.15. Map of netto water erosion 2002 in ton/ha/year. Negative values indicate soil erosion occurrence and positive values indicate deposition



Figure 5.16. Map of netto water erosion 2014 in ton/ha/year. Negative values indicate soil erosion occurrence and positive values indicate deposition

5.3. Soil erosion on different land use types

This sub section was aimed to identify the susceptibility of land use types toward soil erosion. The susceptibility was detected from the largest proportion of high rate of soil erosion in a land use type. High rate of soil erosion means that the material in such land use type is more detachable for several reasons. Therefore, the analysis was focused on annual soil erosion in range of 100 ton/ha to 500 ton/ha and > 500 ton/ha. And the erosion data is using soil erosion data of 2014 and 2002.

Table 5.13 shows the proportion of soil erosion in each land use type. Based on Table 5.13, the susceptible land uses on soil erosion were vegetable croplands and agro-forestry. Because most of the erosion occurrences were dominated by these land use types. For instance, in 2014, 36% and 38% of the erosion ranging from 100 to 500 tons/year and >500 tons/year occurred in vegetable croplands respectively. And, Agro-forestry was the source of such soil erosion categories by 28% to 31%. Meanwhile, plantation forest and shrub rangeland were two least erosion sources. The same pattern with different numbers was also shown by erosion in 2002.

		Erosion coverage area 2014 by land use types								
Erosion	А	В	C	D	E	F	G			
(ton/ha/year)	(%)	(%)	(%)	(%)	(%)	(%)	(%)			
>-500	28	9	36	2	18	6	0			
-500 to - 100	31	10	38	5	7	8	1			
-100 to - 50	37	9	28	8	4	12	1			
-50 to - 10	38	6	19	9	3	21	3			
-10 to - 5	39	5	14	7	4	24	7			
-5 to -2	44	4	12	5	4	22	9			
-2 to 0	48	2	10	3	3	18	16			
		Eı	osion covera	ge area 2002	by land use	types				
Erosion	А	В	C	D	E	F	G			
(ton/ha/year)	(%)	(%)	(%)	(%)	(%)	(%)	(%)			
>-500	28	6	31	10	15	9	1			
-500 to - 100	31	6	29	13	7	11	2			
-100 to - 50	33	5	24	14	6	15	4			
-50 to - 10	35	4	21	11	6	18	6			
-10 to - 5	41	3	18	8	6	17	8			
-5 to -2	46	2	13	7	4	14	13			
-2 to 0	47	2	15	6	6	10	15			

Table 5.13. Erosion coverage area 1994 to 2014 by land use types

A= Agro-forestry, B= Settlement/infrastructure, C=Vegetable cropland, D= Plantation forest, E= Paddy field, F= Plantation, G=Shrub rangeland

The reasons why vegetable croplands and agroforesty were more susceptible on soil erosion than other types of land use was because the two land use types have less vegetation cover than others. Vegetable croplands that were dominated by potatoes and other vegetables were only covered by thin canopy. The same thing also applied for agroforestry that most of the agroforesty area was dominated by the agricultural crops such as corn, cassava, chocolate, and mixed with albasia, bamboo, and others which have less canopy cover. The vegetation is very prominent in determining the soil erosion by water (Morgan & Duzant, 2008). The vegation canopy is effective in controlling run-off effect on soil erosion (Morgan & Duzant, 2008). Consequently erosion rate in forested area is lower than less vegetated area (Shrestha, 1997). Moreover, the position of vegetable croplands and agro-forestry that lie in slope ranges of 30% to 70% (steep slope) aggravate the soil erosion occurrence. The steep slopes is very susceptible to intensive denudational process, such as erosion under forest cover, creep and landslides (V. Zuidam & A, 1985).

On the other hand, plantation forest and shrub rangeland were two land use types where the high rate of soil erosion occurred in small coverage. High vegetation cover in plantation forest and shrub rangeland reduces run-off velocity (Morgan & Duzant, 2008). Despite most of which location is in sloping area, vegetation cover is effective in reducing soil erosion (Morgan & Duzant, 2008).

Paddy field mostly showed small coverage area of high erosion. However, a quite distinctive pattern appeared in erosion >500 ton/ha where 18% (2014) and 15% (2002) of the such erosion rate occurred in paddy field. It could happen due to short three phases of paddy field: paddy field under rice cropping, fallow and green manure planting, especially for terraced paddy field (Chen et al., 2012). The high soil erosion mostly occurs in paddy field under fallow and green manure planting which are vulnerable to collapse of embankment and it increased soil erosion (Chen et al., 2012). In addition, during these periods, run-off in terraced paddy field is also high and triggers more sediment (Chen et al., 2012). On the other hand, most low rate of soil erosion in paddy field as shown in Table 5.13 is because paddy fields act as sediment traps and reduce soil erosion in terraced area (Sukristyonubowo et al., 2010). Moreover, most locations of paddy field are in the flat areas.

5.4. Dynamic tolerable soil loss

Tolerable soil loss or soil loss tolerance is defined as the maximum soil loss by erosion that allows optimum crop productivity (Wischmeier & Smith, 1978). Tolerable soil loss is the quantity of soil surface that can be reduced without decreasing crop productivity in function of time and position (Stamey & Smith, 1964). By this definition, soil loss tolerance is dependent on the soil profile thickness (Li et al., 2009).

Studies about tolerable soil loss are aimed mainly to provide a basis for decision making for soil conservation planning (Wischmeier & Smith, 1978). Soil erosion information which is combined with tolerable soil loss will give guideline of actions to be undertaken in specified limit of soil loss for soil conservation (Wischmeier & Smith, 1978). Any crop management that allows soil erosion less than tolerable soil loss is said to be a satisfactory erosion control (Wischmeier & Smith, 1978). Hence, tolerable soil loss information is important to preserve the soil productivity and environmental security for a long term (Li et al., 2009).

Most tolerable soil loss assessments merely use soil depth and soil formation rate as determinants. And the value of tolerable soil loss is mostly uniform for such large area. Consequently, tolerable soil loss information tends to be static and ignores the dynamic of soil erosion and the effect of soil erosion process (soil loss and deposition) on soil depth itself. Moreover, it is not a function of position. Therefore, it does not correspond with Stamey & Smith (1964) saying that tolerable soil loss must be adaptable with erosion and renewal rates of any soil characteristics and it also must be in a function of position. In addition, tolerable soil loss information that only relies on soil depth and soil formation rate can mislead the users in understanding the tolerable soil loss information. When tolerable soil loss is only focused on soil thickness, it may look as such thick of soil. And it may lead to a worse practice of soil utilizations. But in fact, when annual soil erosion is involved, such thick of soil may have completely removed due to the high rate of soil erosion.

For that reasons, this research applied soil erosion spatial information from the Watem/Sedem erosion model that consisted of soil erosion and deposition rate, incorporating with soil depth needed by farmers for producing optimum crop productivity and soil formation rate. The soil depth and soil erosion were in spatial information (function of position). The soil depth information was based on farmer's perspective as explained in Chapter 4.

Although bias may have happened in farmer's judgment estimating the soil depths, however, the use of farmer's perspective in land degradation judgment has advantages (Stocking & Murnaghan, 2000): the judgment is more realistic of actual field level processes, and the assessment involved the ultimate client for the work, farmers. Meanwhile, soil formation rate in this research relied on single value of 2.5 mm/year (Arsyad, 1989).

The involvement of annual soil loss as part of tolerable soil assessment results in soil loss tolerance which is dynamic following soil erosion. Deposition contributed positively on the soil loss tolerance and erosion will reduce the soil loss tolerance. And by itself, the definition of tolerable soil loss in this research shifts to accommodate the annual soil erosion effect. The **Dynamic Tolerable Soil Loss** is defined as the amount of annual allowable soil loss that guarantees the optimum production of crops by considering certain soil resources period and assigned annual soil erosion rate. By this definition, tolerable soil loss is the allowable amount of soil loss after the process of annual soil erosion by taking into account the period of soil resource usage and soil formation rate. The intolerable soil loss occurs when there is no more soil depth available after the process of annual soil erosion. So, tolerable soil loss is not only determined by the soil depth and soil formation rate but also by annual soil erosion rate.

The period of soil erosion was determined as 25 years and 400 years. The use of the two soil erosion period was based on Morgan (2005) and (Arsyad, 1989). Morgan (2005) suggested the assessment of tolerable soil loss should be in period of 20 to 25 years (with the mean of tolerable soil loss value is 11 ton/ha and or 2 ton/ha for thin soil and sensitive area). Meanwhile, Arsyad (1989) suggested period of 400 years in tolerable soil loss assessment. 400 years is considered to be an enough time to maintain the soil sustainability. The same period of time was also applied by (Setiawan, 2012) who conducted tolerable soil loss assessment in Wonosobo District, which is still in upper part of Serayu watershed. After all, the use of two erosion periods was merely meant to give alternatives for various stakeholders depending on their interest in soil management (Bui et al., 2011).

The result of tolerable soil loss based on 400 years of erosion period showed that 25% of Merawu watershed area experienced intolerable soil loss (Table 5.14). It means any kinds of annual soil erosion rate in those areas are potential to deteriorate soil productivity because of the reduction water storage capacity which crucial for crops (Li et al., 2009) The areas were distributed in all sub districts within the catchment (Figure 5.17). Pejawaran and Wanayasa were two sub districts whose areas were the largest areas affected by intolerable soil loss with 1900 and 1400 ha respectively (Table 5.15). The dominant tolerable soil was in range of 2.6 mm to 5 mm and 0.1 mm to2.5 mm with 38% and 30% of the catchment area respectively that was distributed in all area os the catchment. High value of tolerable soil loss (in range of 5 mm up) was dominated by Southern part of Wanayasa, Madukara, Pagentan, Banjarmangu sub districts.

Soil loss tolerance (mm/year)	Area (ha)
No tolerance (0)	5837.8
0.1 to 2.5	6914.0
2.6 to 5	9017.3
5.1 to 10	1188.4
>10.1	344.8

Table 5.14. Soil loss tolerance coverage areas based on 400 years of erosion periods

Table 5.15. Spatial distribution by sub districts of soil loss tolerance based on 400 years of erosion period

Soil loss		Soil loss tolerance area coverage								
tolerance	1	2	3	4	5	6	7	8		
(mm/year)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)		
Intolerable	1955	1421	632	646	333	209	406	235		
0.1 to 2.5	2540	1205	374	1289	629	284	331	261		
2.6 to 5	3630	1302	445	1186	677	547	637	590		
5.1 to 10	289	9	7	8	3	209	473	188		
>10	129	70	26	36	23	22	21	19		

1= Wanayasa, 2= Pejawaran, 3= Batur, 4= Karangkobar, 5= Kalibening, 6= Madukara, 7= Pagentan, 9= Banjarmangu



Figure 5.17. Map of tolerable soil loss based on soil depth for crop productivity for 400 years of erosion period

In 25 years of erosion period, less intolerable soil loss was detected. It was only about 2.5% of the catchment area that was categorized to be intolerable that was spread in all area of the catchment as shown in Table 5.16 and Table 5.17. Most of the

intolerable soil loss occurred in Karangkobar and Wanayasa Sub districts. In general, the catchment was dominated by tolerable soil loss in range of 20.1 mm to 40 mm that was distributed in all area of the catchment. The area of intensive tillage for vegetables such as in Batur, Pejawaran and Wanayasa Sub districts still had excess of soil depth. This happened due to the thickness of the soil. The complete spatial distribution of tolerable soil loss is indicated by the table and the Figure 5.18.

Soil loss tolerance (mm/year)	На
No tolerance	602.4
0.1 to 2.5	178.9
2.6 to 5	189.3
5.1 to 10	1122.5
10.1 to 20	5158.9
20.1 to 40	10037.8
> 40.1	6012.6

Table 5.16. Soil loss tolerance coverage areas based on 25 years of erosion period

Table 5.17	. Spatial	distribution	by sub	districts	of soil	loss	tolerance	based	on 25	years of
			e	rosion pe	eriod					

Soil loss		Soil loss tolerance area coverage								
tolerance	1	2	3	4	5	6	7	8		
(mm/year)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)	(Ha)		
Intolerable	206	78	46	135	93	4	19	14		
0.1 to 2.5	33	17	9	24	84	2	3	2		
2.6 to 5	59	47	19	24	16	3	6	4		
5.1 to 10	630	102	41	172	52	29	31	25		
10.1 to 20	1224	634	269	1535	1060	115	146	130		
20.1 to 40	4281	2874	965	869	315	200	117	540		
>40	2109	254	137	407	45	920	1545	578		

1= Wanayasa, 2= Pejawaran, 3= Batur, 4= Karangkobar, 5= Kalibening, 6= Madukara, 7= Pagentan, 9= Banjarmangu



Figure 5.18. Map of tolerable soil loss based on soil depth for crop productivity for 25 years of erosion period

The results of the tolerable soil loss in two erosion periods show that some area needs extra attention in soil management since they have become intolerable toward soil erosion, especially if the soil sustainability is hoped to last for 400 years. The work of Setiawan (2012) showed similar results with the result 400 years erosion period assessment, where he found the tolerable soil loss was in range of 2.1 mm to 6.5 mm in 4 plots of assessment.

5.5. The effect of soil loss on crop productivity

Noticing the result of tolerable soil loss both in 25 and 400 years of erosion periods, some areas in Merawu watershed have been suffering from intolerable soil loss. It means that soil loss is potential to affect soil quality that leads to the decline of crop productivity.

To get information whether soil loss has affected crop productivity, 43 farmers have been interviewed asking about their crop yields the last 20 years. The interviewees consisted of 4 groups: farmers of vegetable croplands (potatoes, carrot, cabbage, etc), paddy, Salacca (salak), and cassava and maize.

First question was about the trend of crop productivity during the last 20 years. All farmers said that in general their trend of crop yields were relatively stable even though some times the crop yields were up and down due to the weather dynamic, plant diseases, seed quality, and the introduction of new farming techniques by Government's officers. New farming techniques mostly gave positive effect on their crop yields.

The amount of fertilizers used during the last 20 years was also relatively the same (in term of dosages). Even, for cassava, maize, and Salacca plantation, the farmers did not rely on the fertilizers too much. The application of the fertilizers was only when they could afford it. It means that the farmers did not try to boost their crop productivity using fertilizers. Therefore, it can be concluded that so far according to the the farmers, soil loss has not yet degraded the quality of the soil in spite of the high soil erosion and intolerable soil loss detected, that is reflected from the same amount of harvest they can earn every year.

Major contributing factor to this phenomenon is suspected due to thick and fertile soil in Merawu watershed. Most respondents confirmed that in average the thickness of fertile soil is more than 1 meter. The real soil thickness is more than that. The second, farmers are introduced to better seeds and better farming techniques that can give better yields. Compared to early periods of farming (20 years ago), farmers acknowledge that they have been informed about proper technique and seed selection. That's why the effect of soil erosion is not noticeable by farmers.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Based on the results of analyses, the following conclusions can be made:

- 1. During 1994 to 2014, 50% of land use has changed in Merawu watershed. The changes were dominated by the changes among agricultural land use types. The dominant trajectories are from and to agro-forestry and vegetable croplands.
- 2. Soil erosion has succeeded to be modeled by using Watem/Sedem erosion modeling. The result of the model validation showed that the accuracy of the erosion modeling compared to the recorded actual sediment in Merawu outlet was 0.75 and coefficient determination R^2 was 0.56.
- 3. The highest soil erosion rate occurred in 1994 (3,018,582 ton), and the lowest occurred in 2002 (1,229,729 ton). Whereas in 2014, sediment delivery rose again up to 1,348,185 ton.
- 4. In relation with soil erosion, land use change affected the dynamic of soil erosion. Less plantation forest in 1994 and large agricultural area have delivered sediment to the catchment outlet higher among others (2002 and 2014). And more forest coverage in 2002 has decreased soil erosion.
- 5. 25% of the area of Merawu watershed based on present soil erosion is affected by intolerable soil loss rate by assuming that the expected optimum crop productivity period was 400 years. But if the period was shortened to 25 years, it was only 2.5% of the area that was categorized to be in intolerable soil loss.
- 6. Despite the existence of intolerable soil loss, farmers of Merawu watershed did not feel that there was a decline in their crop productivity

6.2. Recommendations

Based on the conclusion made, recommendations were suggested as following:

- The land use change that is mostly affected by agricultural activities needs to be projected to figure out where the land use change leads in the future. It is useful to plan strategies in land rehabilitation and to anticipate the possibility of erosion risk triggered by land use changes.
- 2. High soil erosion in Merawu watershed is potential to remove most of top soil surfaces and affect soil quality as explained previously. Even though farmers have not yet felt the influence of soil erosion on crop productivity, however a more detailed research scale should be conducted, especially in area that

experienced intolerable soil loss, to figure out how bad soil loss has affected soil quality.

3.

A suitable soil conservation technique should be formulated in Merawu watershed considering the high soil loss and the irreplaceable agricultural practice. Setiawan, (2012) suggested two kinds of soil conservation techniques: terrace risers with stone and terrace riser with grass. These two conservation techniques can be a good start to formulate the best technique for Merawu watershed.

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APPENDICES



Appendix 1. Map of land use reference samples position



Appendix 2. Map of training sample guide position



Appendix 3. Map of soil samples positions

Appendix 4. Rationality change detection assessment samples

	pluitutioi	LAND USE		Bivela	Sin do Tu
No	1004	LAND USI	2014	changes	Rules
1	1994	2002	2014	TDUE	D1- 1
1	6	6	6	TRUE	Rule I
2	3	3	3	TRUE	Rule I
3	3	3	3	TRUE	Rule I
4	1	1	1	TRUE	Rule I
5	6	6	6	TRUE	Rule 1
6	1	1	6	TRUE	Rule 2
7	2	2	1	FALSE	Rule 3
8	1	1	1	TRUE	Rule 1
9	1	3	3	TRUE	Rule 2
10	1	1	1	TRUE	Rule 1
11	3	3	2	TRUE	Rule 2
12	1	1	1	TRUE	Rule 1
13	3	3	3	TRUE	Rule 1
14	1	1	6	TRUE	Rule 2
15	6	6	6	TRUE	Rule 1
16	1	1	1	TRUE	Rule 1
17	3	3	3	TRUE	Rule 1
18	1	1	1	TRUE	Rule 1
19	3	1	1	TRUE	Rule 2
20	3	3	3	TRUE	Rule 1
21	1	3	1	FUZZY	Rule 4
22	4	4	4	FUZZY	Rule 1
23	6	1	6	FUZZY	Rule 4
24	3	3	3	FUZZY	Rule 1
25	3	1	3	FUZZY	Rule 4
26	3	3	1	FUZZY	Rule 2
27	6	5	6	FUZZY	Rule 4
28	3	3	3	FUZZY	Rule 1
29	1	1	6	FUZZY	Rule 2
30	1	2	2	FUZZY	Rule 2
31	3	3	3	FUZZY	Rule 1
32	4	4	1	FUZZY	Rule 2
33	1	1	6	FUZZY	Rule 2
34	1	1	1	FUZZY	Rule 1
35	6	5	1	FUZZY	Rule 5
36	1	6	6	FUZZY	Rule 2
37	3	1	3	FUZZY	Rule 4
38	3	3	3	FUZZY	Rule 1

1= agro-forestry, 2=settlements/infrastructure, 3= vegetable croplands, 4= plantation forest, 5= paddy field, 6=plantation, 7= shrub rangeland

39	1	4	6	FUZZY	Rule 5
40	1	1	1	FUZZY	Rule 1
41	5	2	1	FUZZY	Rule 3
42	6	4	1	FUZZY	Rule 5
43	1	6	6	FUZZY	Rule 2
44	6	3	1	FUZZY	Rule 5
45	3	1	3	FUZZY	Rule 4
46	5	6	6	FUZZY	Rule 2
47	7	1	7	FUZZY	Rule 4
48	5	6	2	FUZZY	Rule 5
49	3	3	3	FUZZY	Rule 1
50	5	5	5	FUZZY	Rule 1
51	7	7	7	FUZZY	Rule 1
52	6	6	6	FUZZY	Rule 1
53	5	6	6	FUZZY	Rule 2
54	3	3	3	FUZZY	Rule 1
55	1	4	1	FUZZY	Rule 4
56	2	2	2	FUZZY	Rule 1
57	1	3	4	FUZZY	Rule 5
58	1	6	6	FUZZY	Rule 2
59	2	5	5	FUZZY	Rule 3
60	1	4	4	FUZZY	Rule 2
61	1	4	1	FUZZY	Rule 4
62	4	7	7	FUZZY	Rule 2
63	6	6	6	FUZZY	Rule 1
64	3	3	3	FUZZY	Rule 1
65	2	2	2	FUZZY	Rule 1
66	1	7	7	FUZZY	Rule 2
67	1	1	1	FUZZY	Rule 1
68	1	1	6	FUZZY	Rule 2
69	3	1	1	FUZZY	Rule 2
70	7	7	7	FUZZY	Rule 1
71	4	4	4	FUZZY	Rule 1
72	1	1	1	FUZZY	Rule 1
73	6	6	6	FUZZY	Rule 1
74	3	3	3	FUZZY	Rule 1
75	4	7	4	FUZZY	Rule 4
76	3	3	3	FUZZY	Rule 1
77	3	3	3	FUZZY	Rule 1
78	1	1	1	FUZZY	Rule 1
79	1	7	1	FUZZY	Rule 4
80	3	3	3	FUZZY	Rule 1
81	1	7	1	FUZZY	Rule 4

82	3	3	3	FUZZY	Rule 1
83	1	1	1	FUZZY	Rule 1
84	3	1	1	FUZZY	Rule 2
85	4	4	4	FUZZY	Rule 1
86	1	4	4	FUZZY	Rule 2
87	1	3	1	FUZZY	Rule 4
88	1	1	1	FUZZY	Rule 1
89	1	1	1	FUZZY	Rule 1
90	1	1	1	FUZZY	Rule 1
91	1	3	3	FUZZY	Rule 2
92	7	1	7	FUZZY	Rule 4
93	1	1	1	FUZZY	Rule 1
94	3	3	3	FUZZY	Rule 1
95	1	1	3	FUZZY	Rule 2
96	7	3	3	FUZZY	Rule 2
97	1	1	1	FUZZY	Rule 1
98	1	1	1	FUZZY	Rule 1
99	1	1	3	FUZZY	Rule 2
100	2	2	2	FUZZY	Rule 1
101	3	1	1	FUZZY	Rule 2
102	1	1	2	FUZZY	Rule 2
103	3	3	1	FUZZY	Rule 2
104	5	5	5	FUZZY	Rule 1
105	6	6	1	FUZZY	Rule 2
106	1	1	1	FUZZY	Rule 1
107	1	4	1	FUZZY	Rule 4
108	3	3	3	FUZZY	Rule 1
109	3	3	1	FUZZY	Rule 2
110	1	6	6	FUZZY	Rule 2
111	4	4	4	FUZZY	Rule 1
112	4	7	7	FUZZY	Rule 2
113	6	1	6	FUZZY	Rule 4
114	3	3	3	FUZZY	Rule 1
115	7	3	7	FUZZY	Rule 4
116	1	6	6	FUZZY	Rule 2
117	1	4	4	FUZZY	Rule 2
118	4	1	1	FUZZY	Rule 2
119	1	3	6	FUZZY	Rule 5
120	1	1	1	FUZZY	Rule 1
121	3	1	3	FUZZY	Rule 4
122	1	6	6	FUZZY	Rule 2
123	1	1	1	FUZZY	Rule 1
124	2	6	6	FUZZY	Rule 2

125	1	6	6	FUZZY	Rule 2
126	5	5	5	FUZZY	Rule 1
127	1	1	6	FUZZY	Rule 2
128	6	6	1	FUZZY	Rule 2
129	5	5	5	FUZZY	Rule 1
130	1	1	1	FUZZY	Rule 1
131	1	3	4	FUZZY	Rule 5
132	3	3	3	FUZZY	Rule 1
133	1	3	1	FUZZY	Rule 4
134	1	1	1	FUZZY	Rule 1
135	1	1	1	FUZZY	Rule 1
136	1	1	1	FUZZY	Rule 1
137	6	6	6	FUZZY	Rule 1
138	7	7	7	FUZZY	Rule 1
139	3	3	3	FUZZY	Rule 1
140	1	1	6	FUZZY	Rule 2
141	2	3	2	FUZZY	Rule 3
142	1	1	6	FUZZY	Rule 2
143	6	6	6	FUZZY	Rule 1
144	6	6	6	FUZZY	Rule 1
145	6	6	6	FUZZY	Rule 1
146	3	1	3	FUZZY	Rule 4
147	1	3	1	FUZZY	Rule 4
148	3	3	3	FUZZY	Rule 1
149	3	3	3	FUZZY	Rule 1
150	1	1	1	FUZZY	Rule 1
151	1	1	1	FUZZY	Rule 1
152	3	1	1	FUZZY	Rule 2
153	6	6	6	FUZZY	Rule 1
154	3	3	3	FUZZY	Rule 1
155	3	2	2	FUZZY	Rule 2
156	1	1	1	FUZZY	Rule 1
157	7	7	7	FUZZY	Rule 1
158	1	6	6	FUZZY	Rule 2
159	1	1	1	FUZZY	Rule 1
160	3	3	3	FUZZY	Rule 1
161	1	1	2	FUZZY	Rule 2
162	3	1	1	FUZZY	Rule 2
163	1	2	3	FUZZY	Rule 3
164	1	1	1	FUZZY	Rule 1
165	6	6	6	FUZZY	Rule 1
166	4	7	7	FUZZY	Rule 2
167	1	1	1	FUZZY	Rule 1

168	4	4	4	FUZZY	Rule 1
169	6	6	5	FUZZY	Rule 2
170	3	3	3	FUZZY	Rule 1
171	1	1	3	FUZZY	Rule 2
172	5	5	5	FUZZY	Rule 1
173	1	1	6	FUZZY	Rule 2
174	3	3	3	FUZZY	Rule 1
175	1	1	3	FUZZY	Rule 2
176	1	6	6	FUZZY	Rule 2
177	3	1	1	FUZZY	Rule 2
178	1	1	1	FUZZY	Rule 1
179	3	3	4	FUZZY	Rule 2
180	1	1	1	FUZZY	Rule 1
181	1	3	1	FUZZY	Rule 4
182	4	4	4	FUZZY	Rule 1
183	1	3	1	FUZZY	Rule 4
184	6	6	6	FUZZY	Rule 1
185	7	7	7	FUZZY	Rule 1
186	7	7	7	FUZZY	Rule 1
187	5	5	5	FUZZY	Rule 1
188	3	3	3	FUZZY	Rule 1
189	3	1	3	FUZZY	Rule 4
190	3	3	3	FUZZY	Rule 1
191	6	1	1	FUZZY	Rule 2
192	1	4	1	FUZZY	Rule 4
193	1	1	1	FUZZY	Rule 1
194	6	1	6	FUZZY	Rule 4
195	1	3	1	FUZZY	Rule 4
196	1	4	1	FUZZY	Rule 4
197	6	6	6	FUZZY	Rule 1
198	1	1	1	FUZZY	Rule 1
199	6	6	6	FUZZY	Rule 1
200	3	3	3	FUZZY	Rule 1
201	7	3	7	FUZZY	Rule 4
202	1	6	6	FUZZY	Rule 2
203	5	5	5	FUZZY	Rule 1
204	1	1	1	FUZZY	Rule 1
205	3	1	3	FUZZY	Rule 4
206	5	6	5	FUZZY	Rule 4
207	3	1	3	FUZZY	Rule 4
208	3	3	3	FUZZY	Rule 1
209	5	6	6	FUZZY	Rule 2
210	3	1	1	FUZZY	Rule 2

211	1	1	1	FUZZY	Rule 1	
212	1	6	6	FUZZY	Rule 2	
213	2	6	6	FUZZY	Rule 2	
214	1	1	3	FUZZY	Rule 2	
215	3	3	3	FUZZY	Rule 1	
216	3	1	1	FUZZY	Rule 2	
217	1	1	1	FUZZY	Rule 1	
218	3	1	1	FUZZY	Rule 2	
219	3	1	1	FUZZY	Rule 2	
220	4	4	4	FUZZY	Rule 1	
221	1	3	3	FUZZY	Rule 2	
222	6	6	6	FUZZY	Rule 1	
223	2	2	2	FUZZY	Rule 1	
224	3	3	2	FUZZY	Rule 2	
225	1	1	6	FUZZY	Rule 2	
226	1	6	1	FUZZY	Rule 4	
227	1	6	6	FUZZY	Rule 2	
228	3	3	3	FUZZY	Rule 1	
229	1	4	4	FUZZY	Rule 2	
230	3	2	2	FUZZY	Rule 2	
231	4	4	4	FUZZY	Rule 1	
232	1	4	4	FUZZY	Rule 2	
233	7	7	4	FUZZY	Rule 2	
234	3	3	3	FUZZY	Rule 1	
235	1	3	2	FUZZY	Rule 5	
236	1	1	1	FUZZY	Rule 1	
237	1	1	1	FUZZY	Rule 1	
238	1	1	1	FUZZY	Rule 1	
239	1	3	3	FUZZY	Rule 2	
240	6	6	6	FUZZY	Rule 1	
241	6	5	5	FUZZY	Rule 2	
242	1	3	3	FUZZY	Rule 2	
243	1	4	4	FUZZY	Rule 2	
244	4	7	7	FUZZY	Rule 2	
245	4	4	4	FUZZY	Rule 1	
246	1	1	1	FUZZY	Rule 1	
247	7	7	7	FUZZY	Rule 1	
248	1	1	1	FUZZY	Rule 1	
249	4	4	4	FUZZY	Rule 1	
250	3	3	3	FUZZY	Rule 1	
251	6	6	1	FUZZY	Rule 2	
252	1	3	1	FUZZY	Rule 4	
253	4	4	7	FUZZY	Rule 2	
2	54	4	4	4	FUZZY	Rule 1
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25	55	5	5	5	FUZZY	Rule 1
25	56	4	4	4	FUZZY	Rule 1
25	57	6	6	2	FUZZY	Rule 2
25	58	3	1	1	FUZZY	Rule 2
2	59	1	1	1	FUZZY	Rule 1
20	60	3	2	2	FUZZY	Rule 2
20	61	6	6	6	FUZZY	Rule 1
20	62	3	6	1	FUZZY	Rule 5
20	63	3	1	1	FUZZY	Rule 2
20	64	5	5	5	FUZZY	Rule 1
20	65	3	3	2	FUZZY	Rule 2
20	66	1	1	1	FUZZY	Rule 1
20	67	3	1	1	FUZZY	Rule 2
20	68	1	1	3	FUZZY	Rule 2
20	69	3	1	1	FUZZY	Rule 2
2	70	3	3	2	FUZZY	Rule 2
2	71	1	1	1	FUZZY	Rule 1
2	72	1	1	2	FUZZY	Rule 2
2	73	3	1	3	FUZZY	Rule 4
2	74	4	1	1	FUZZY	Rule 2
2	75	3	1	1	FUZZY	Rule 2
2	76	1	1	1	FUZZY	Rule 1
2	77	1	6	1	FUZZY	Rule 4
2	78	4	1	1	FUZZY	Rule 2
2	79	6	1	6	FUZZY	Rule 4
28	80	3	3	3	FUZZY	Rule 1
28	81	3	3	3	FUZZY	Rule 1
28	82	6	6	6	FUZZY	Rule 1
28	83	6	6	6	FUZZY	Rule 1
28	84	1	5	5	FUZZY	Rule 2
28	85	3	3	3	FUZZY	Rule 1
28	86	3	3	3	FUZZY	Rule 1
28	87	4	7	4	FUZZY	Rule 4
28	88	3	1	1	FUZZY	Rule 2
28	89	1	3	3	FUZZY	Rule 2
29	90	1	4	4	FUZZY	Rule 2
29	91	1	1	1	FUZZY	Rule 1
29	92	1	7	1	FUZZY	Rule 4
29	93	3	3	3	FUZZY	Rule 1
29	94	6	1	1	FUZZY	Rule 2
29	95	4	4	4	FUZZY	Rule 1
20	96	3	1	1	FUZZY	Rule 2

297	3	3	3	FUZZY	Rule 1
298	1	1	1	FUZZY	Rule 1
299	7	4	1	FUZZY	Rule 5
300	1	1	1	FUZZY	Rule 1

Appendix 5. Land use cl	hange during 1994 to 2002
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Land Use Classes		To 2002									
		Agro-forestry (ha)	Settlements/ infrastructures (ha)	Vegetable croplands (ha)	Plantation forest	Paddy fields (ha)	Plantation	Shrub rangelands (ha)			
	Agro-forestry (ha)	5289.3	131.3	1204.9	891	267.4	953.5	152.8			
	Vegetable croplands (ha)	1723.2	217.5	3708.7	78.2	11	40.8	31.1			
From	Plantation Forest (ha)	411.5	4.0	174	837.8	0.3	1.44	404.3			
1994	Paddy fields (ha)	19.2	30.1	31.7	7.1	1022.5	215.1	3.2			
	Plantation (ha)	442.8	44.4	97.6	177.9	154.1	2256.5	1.3			
	Shrub rangelan (ha)	175.8	11.6	131.5	253.4	3.33		787.2			

Appendix 6. Land use changes during 2002 to 2014

		To 2014								
	Land Use Classes	Agro-forestry (ha)	Settlements and infrastructure (ha)	Vegetable cropland (ha)	Plantation forest (ha)	Paddy field (ha)	Plantation (ha)	Shrub rangeland (ha)		
	Agro-forestry (ha)	5777.5	107.2	1122.1	121.2	13.4	867.5	117.2		
	Vegetable croplands (ha)	1509.5	260.6	3423.4	113.8	20.2	76.8	62.0		
From	Plantation forest (ha)	695.9	2.4	37.7	1060.6	1.5	185.8	268.0		
2002	Paddy fields (ha)	377.1	53.5	50	6.6	830.1	207.8	2.7		
	Plantation	583.5	123.1	26.0	15.8	124.6	2680.6			
	Shrub rangelands (ha)	256.1	0.4	37.8	183.6	0.2	2.5	909.6		

		Slope Class (%)							
_									
La	0-2	2-7	7-15	15-30	30-70	70-140	<140		
	Agro-forestry (ha)	108.36	354.6	819.36	2121.48	2101.4	190.26	81.99	
	Settlement/Infrastructure (ha)	5.22	14.4	26.19	43.74	17.01	0.54	0.09	
	Vegetable cropland (ha)	27.54	94.23	209.88	454.5	326.61	7.65	1.71	
Agro-forestry	Plantation forest (ha)	0.09	1.71	7.56	36.72	70.11	4.77	0.27	
	Paddy Field (ha)		0.36	0.81	5.13	5.85	1.26		
	Plantation (ha)	5.76	26.19	86.4	347.31	361.44	36.99	3.42	
	Shrub rangeland (ha)	0.18	4.59	12.15	40.86	54.45	4.95		
	Agro-forestry (ha)	42.39	152.55	336.15	614.34	331.47	16.2	16.38	
	Settlement/Infrastructure (ha)	9.09	51.48	96.57	86.85	14.67	0.72	1.26	
Vegetable	Vegetable cropland (ha)	124.74	402.84	841.77	1334.88	706.14	6.48	6.57	
anonland	Plantation forest (ha)	0.9	4.68	10.26	46.35	47.16	4.5		
cropiand	Paddy Field (ha)	0.18	1.35	5.49	12.51	0.36	0.27		
	Plantation (ha)	1.08	4.77	12.33	42.75	15.03	0.63	0.18	
	Shrub rangeland (ha)		2.34	6.39	20.43	32.67	0.18		
	Agro-forestry (ha)	1.17	6.21	21.33	127.62	440.1	79.47	19.98	
	Settlement/Infrastructure (ha)	,	0.21	0.18	0.63	1.44	0.18	17.70	
Plantation	Vegetable cropland (ha)	0.18	0.9	1.35	9.54	22.32	3.15	0.27	
Forest	Plantation forest (ha)	0.18	2.16	17.1	129.33	696.15	208.08	7.56	
	Paddy Field (ha)				1.08	0.45			
	Plantation (ha)	0.09	1.17	5.85	32.49	130.05	15.3	0.81	
	Shrub rangeland (ha)	0.36	1.62	4.59	46.08	184.41	30.96		
	Agro-forestry (ha)	3.51	24.39	79.2	203.13	65.7	1.17		
	Settlement/Infrastructure (ha)	4.41	17.19	14.31	15.3	2.34			
	Vegetable cropland (ha)	0.45	4.86	11.7	26.19	6.75			
Paddy field	Plantation forest (ha)			0.63	2.61	3.24	0.09		
	Paddy Field (ha)	107.46	207.81	159.48	239.22	114.84	1.26		
	Plantation (ha)	0.9	8.28	36.09	129.33	32.85	0.36		
	Shrub rangeland (ha)		0.18	0.63	1.8	0.09			
	Agro-forestry (ha)	4.68	23.67	86.13	278.46	172.89	15.75	1.89	
	Settlement/Infrastructure (ha)	2.97	18.36	31.77	55.26	14.76			
Plantation	Vegetable cropland (ha)	0.45	2.43	8.19	9.72	4.05	0.72	0.45	
1 minution	Plantation forest (ha)		0.18	1.35	5.58	7.47	1.26		
	Paddy Field (ha)	2.25	11.7	23.22	60.21	26.46	0.72		
	Plantation (ha)	14.13	77.49	299.52	1300.05	946.26	42.75	0.36	
	Shrub rangeland (ha)								
	Agro-forestry (ha)	2.43	11.52	28.98	99.09	101.97	11.88	0.27	
	Settlement/Infrastructure (ha)		0.09		0.18	0.09			
Shrub	Vegetable cropland (ha)	0.36	2.34	5.76	12.15	14.4	2.79		
rangeland	Plantation forest (ha)	0.54	1.71	8.55	47.25	108.18	17.37		
	Paddy Field (ha)		0.00		1 4 4	0.00	0.18		
	Plantation (ha)	0.52	0.09	(2.10)	1.44	0.99	<u>(0.01</u>		
	Shrub rangeland (ha)	2.52	15.93	62.19	265.5	494.55	68.94		

Appendix 7. Land use change during 2002 to 2014 based on slope distribution

Appendix 8. Land use change during 1994 to 2002 based on slope distribution

Land use change type Agro-forestry (ha)		Slope Class (%)							
		0-2	2-7	7-15	15-30	30-70	70-140	<140	
	Agro-forestry (ha)	103.41	330.93	746.1	1962.18	1892.9	184.32	69.48	
	Settlement/Infrastructure (ha)	6.39	16.65	29.07	55.35	22.41	1.44		
	Vegetable cropland (ha)	36.72	123.75	267.93	505.26	251.19	12.15	7.92	
	Plantation forest (ha)	1.44	5.58	24.12	157.95	551.43	123.12	27.36	
Agro-forestry	Paddy Field (ha)	1.26	6.39	36.36	154.53	66.78	2.07		
	Plantation (ha)	2.61	18	88.29	492.39	323.1	27	2.16	
	Shrub rangeland (ha)	1.08	4.95	13.77	54.63	64.89	13.23	0.27	
			1.0.0.10						
	Agro-forestry (ha)	36	130.68	302.04	681.75	536.4	19.71	16.65	
	Settlement/Infrastructure (ha)	9.54	45.36	85.41	66.15	10.08	0.18	0.63	
X7 . 11	Vegetable cropland (ha)	134.82	450.36	941.85	1439.37	719.46	7.38	15.48	
Vegetable	Plantation forest (ha)		2.43	4.77	23.85	45.54	1.08	0.54	
cropiands	Paddy Field (ha)		3.42	4.05	3.24	0.27			
	Plantation (ha)	0.63	3.78	9.27	14.31	11.88	0.54	0.36	
	Shrub rangeland (ha)	0.09	2.25	4.95	10.98	12.6	0.27		
	Agro-forestry (ha)	4.23	15.3	44.73	142.74	194.13	9.27	1.08	
	Settlement/Infrastructure (ha)	0.27	0.18	0.18	1.71	1.71			
	Vegetable cropland (ha)	1.08	9.63	20.52	63.72	78.39	0.63		
Plantation	Plantation forest (ha)	0.45	2.43	10.71	97.02	583.92	143.1	0.18	
rorost	Paddy Field (ha)				0.18	0.09			
	Plantation (ha)			0.09	0.09	1.17	0.09		
	Shrub rangeland (ha)	0.9	4.59	17.91	97.02	242.1	41.76		
	Agro-forestry (ha)	0.09	0.27	2.52	10.44	5.85			
	Settlement/Infrastructure (ha)	1.26	4.77	7.56	13.68	2.88			
	Vegetable cropland (ha)	0.36	1.44	7.83	21.15	0.9			
Paddy field	Plantation forest (ha)			0.99	4.32	1.8			
-	Paddy Field (ha)	107.37	218.88	203.85	358.11	133.65	0.63		
	Plantation (ha)	2.88	16.74	37.53	118.62	39.24	0.09		
	Shrub rangeland (ha)			0.09		3.06	0.09		

	Agro-forestry (ha)	1.89	9.72	41.4	168.57	197.91	23.31	
	Settlement/Infrastructure (ha)	1.08	5.22	13.59	18.54	5.76	0.18	
	Vegetable cropland (ha)	1.08	6.66	19.35	33.75	28.71	8.1	
Plantation	Plantation forest (ha)		0.72	6.39	29.97	117.18	23.13	0.54
	Paddy Field (ha)	5.4	15.57	38.16	74.61	20.16	0.18	
	Plantation (ha)	16.2	85.32	292.68	1044.18	785.43	32.67	
	Shrub rangeland (ha)			0.09		0.9	0.36	
	Agro-forestry (ha)	0.72	4.23	15.84	62.1	86.76	6.12	
	Settlement/Infrastructure (ha)		0.27	0.63	3.6	7.11		
	Vegetable cropland (ha)	0.27	3.33	18	54.45	54.9	0.54	
Shrub	Plantation forest (ha)	0.09	0.9	3.33	32.58	169.83	46.71	
Tangeland	Paddy Field (ha)		0.18	0.63	2.16	0.36		
	Plantation (ha)							
	Shrub rangeland (ha)	3.6	19.35	67.77	259.92	391.5	45.09	

Appendix 9. Map of erosivity 2014





Appendix 10. Map of erosivity 2002



Appendix 11. Map of erosivity 1994

Appendix 12. Map of C factor 2014



Appendix 13. Map of C factor 2002





Appendix 14. Map of C factor 1994



Appendix 15. Map of soil erodibility





Appendix 17. Parcel map 2002







Appendix 19. Map of slope distribution



Appendix 20. Part of the result of image classification





Appendix 21. Part of the result of erosion simulation in steep slopes



Appendix 22. Part of the result of erosion simulation in mix terrain (flat and steep slopes)